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NUMERICAL ANALYSIS OF ICE IMPACTS ON AZIMUTH PROPELLER

by

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NUMERICAL ANALYSIS OF ICE IMPACTS ON AZIMUTH PROPELLER

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Incorporating an azimuth/podded propulsion into an ice-capable ship brings concern in the propellers durability and lifecycle. An ice impact model was constructed to have a better understanding of collisions occurring between ice and azimuth/podded propeller for ice operation ships. A typical propeller profile was created using MATLAB and modeled in SolidWorks using realistic material properties. The ANSYS Explicit Dynamics solver was used to simulate the ice-propeller impact. By conducting a parametric study, the ice impact model displayed situations and instances to avoid shortening the use of propellers in ice operation. Therefore, using the ice impact model will allow further study to provide better understanding of the collision a piece of ice has on a propeller.

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LIST OF ACRONYMS AND ABBREVIATIONS

AZIPOD	Azimuth Podded Propulsion
CAD	Computed Aided Design
CPP	Controllable Pitch Propeller
CRP	Contra-Rotating Propeller
DNV	Det Norske Veritas
FPP	Fixed Pitch Propeller
FSICR	Finnish Swedish Ice Class Rules
IACS	International Association of Classification Societies
IEP	Integrated Electric Plant
RPM	Revolutions Per Minute
U.S.	United States
USCG	United States Coast Guard
USN	United States Navy

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I. INTRODUCTION

A. OVERVIEW

As the Arctic climate warms, a progressive amount of Arctic ice breaks up and allows opportunities for vessels to navigate into unresolved territories. It's expected to open up gateways for tourism, research, commercial traffic and resource extraction. Currently, only 4.5 percent of the world's maritime community is warranted to even survive the treacherous Arctic conditions, let alone the polar ice. However, that number is expected to increase up to 10 percent in the ensuing years [1]. With the rising interest and expected increase in traffic in the Arctic region, the United States has vested a strategic objective in the region. The issue at hand is the lack of capable vessels in the United States Navy (USN) or United States Coast Guard (USCG) that can operate within this region. With the current, aging, legacy polar icebreakers operated, by the USCG, acquisition of a new class of heavy icebreaker is needed. This vessel would be capable of enduring the Arctic environment, while still qualified in meeting the surface fleet demands.

B. BACKGROUND

A ships performance in ice has been a topic of review since the early nineteenth century. The review includes the discussion of maximizing systems for vessels to break ice, deriving mathematical expressions and equations for icebreaking, analyzing geometrical appearance of the ship for the best performance in ice and as well as best suited material used for vessels navigating in harsh sea ice environment. Though modern numerical models and new scientific approaches have been made, no clear method exists for predicting the strength of sea ice since it includes characteristics such as the varying salinity, temperature and thickness [2]. While calculating the strength of sea ice may be vague, the damages the ice can have on the ship, particularly the propellers, is of certainty.

Vessels have navigated in waters near ice, clearly knowing the hazard involved with the propeller blade and ice interacting underwater. Propeller ice interaction is one of

the significant concerns and a major issue which should be taken into consideration for the safety of a ship while navigating in ice. This is not limited to vessels that are designed to operate in ice, which usually have some type of ice strengthened propeller, but have been found on all types of vessels including coastal ferries, workboats and fishing boats [3]. When considering icebreaking vessels, the likelihood of achieving damages to the propellers becomes substantially greater. Many of the larger vessels carry spare propeller blades to change out in case of accidents occurring out at sea. Not only can propeller ice interaction result in propeller blade damage, the stress and loads place on the propeller could result in shafting or engine failures [3].

Damages to propeller come from two types of interactions. The first type is ice impact, where a piece of ice travels in the flow of the propeller and impacts the propeller blade or the following blade. The second type is ice milling, when a large piece of ice is cut by the propeller progressively. In either situation, damages can occur such that the propeller becomes ineffective or completely disabled (see Figure 1 and 2).

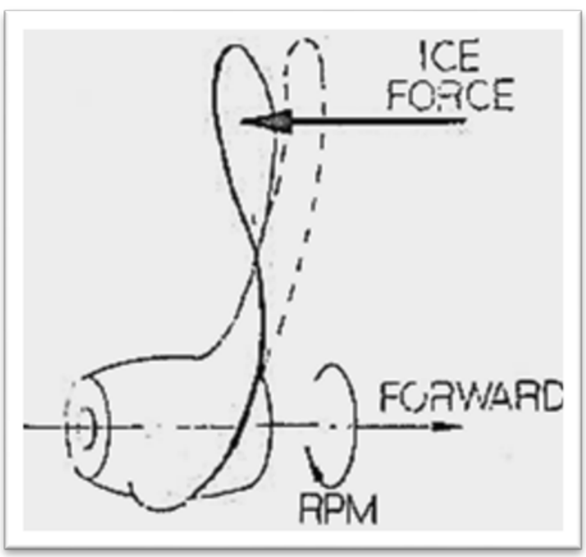

Figure 1. Bent Backwards and Cracked From [3]

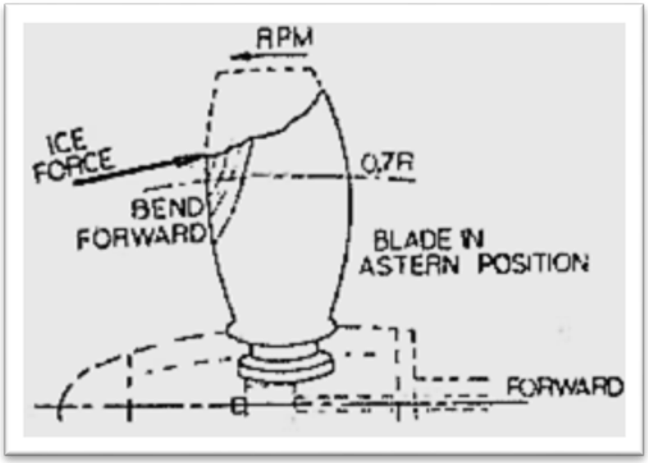

Figure 2. Blade Tips Broken Off From [3]

The selection of material to use for propeller blades can play a critical role. Selection of material for the vessels propeller can be settled upon based on the type of vessel and the environment the vessel will be operating in. Two of the most common materials used for ice propeller design are copper-based alloys or stainless steel propellers. Stainless steel is advantageous due to its strength and resistance to ice impacts, but can fail from brittle factures before any deformation takes place in the blades. Copper-based materials, such as nickel aluminum bronze, tend to bend and distort even when taking severe damages. This allows for the ship to continue operating though at a reduced efficiency [3].

For major developments, the use of azimuth and podded propulsion in ice has opened up new perspectives for vessels in the ice breaking community. To start, the azimuth and podded propulsion concepts allow a propeller to be driven with an electric motor. The propeller is mounted on the hull of the ship through a strut, in which the propeller can rotate a full 360 degrees without any obstruction. This allows for the thrust to be employed in any direction. The need for a rudder is eliminated and the ships maneuverability is greatly improved due to the reduction of drag resistance of underwater appendages (see Figure 3).

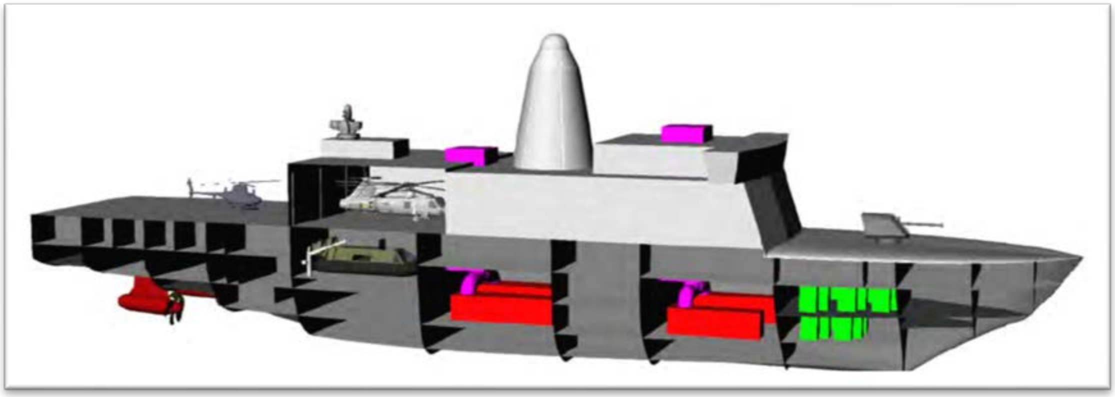

Figure 3. Ship With Azimuth Propulsion From [1]

The widespread use of podded propulsion has dispersed throughout the maritime community. However with the rapid growth and implementation of the concept, little has been tested or standardized to meet the criteria of existing specifications. Some of the common guidelines from International Association of Classification Societies (IACS), Det Norske Veritas (DNV) or Finnish Swedish Ice Class Rules (FSICR), do not have the specified guidelines for vessels with podded propulsion, operating in ice.

C. OBJECTIVE

The objective of this study was to create a generic model for analyzing a propeller ice interaction for an azimuth propulsion system. Vessels that navigate and break ice encounter and test the strength and durability of propellers. By conducting a parametric study, the model produced in this study will demonstrate ice colliding with the propeller blade in various scenarios. Each scenario can help determine and provide better understanding in what conditions of ice interaction for an azimuth propeller blade is detrimental or ideal to the propeller and to the propulsion of a ship.

II. ALTERNATIVE IN PROPULSOR

A. ELECTRIC POWERED PROPULSION PLANTS

The use of podded propulsion could have not become plausible without the implementation of integrated electric plants (IEP). Recent naval vessels, cruise ships, offshore vessels, tankers and icebreakers have preferred integrated electric plants. The all-electric ships utilize electrical propulsion motors and central station power generation that powers all propulsion, thruster, loading equipment and auxiliary systems. IEP designs have become particularly important in ice operations. General vessels with conventional propulsion plant are limited when encountering heavy ice. These vessels require greater power loads when resistance in ice becomes greater. If the required load exceeds the engine's throttle or torque limit, the engine slows and is restricted in its power. This can potentially damage any piece in the drive train of a conventional plant system, which is mechanically interlinked from propeller, shaft, reduction gear and to the engine. In the IEP design, vessels operating in heavy ice require greater torque, therefore having electric motors allows the vessel to modify the ships torque characteristics. The vessel can gain maximum torque at low propeller speed, even if the propeller was to get stuck in ice and be stationary. A vessel with IEP design and podded propulsion, can maintain propellers to rotate in heavy ice conditions and provide thrust to navigate in ice [4].

B. VARIATION OF CONVENTIONAL SHIP PROPELLERS

1. Fixed Pitch Propeller

Just as the name itself describes it, a fixed pitch propeller (FPP) has the blades fixed at a specific pitch angle. Figure 4 illustrates a FPP, which is a very basic propeller setup used in all size vessels. These propellers are normally created from large casings to maintain uniformity as one solid object, though the built-on process is recognized as well. The number of blades for this propeller varies to control cavitation, as well underwater noise [5].

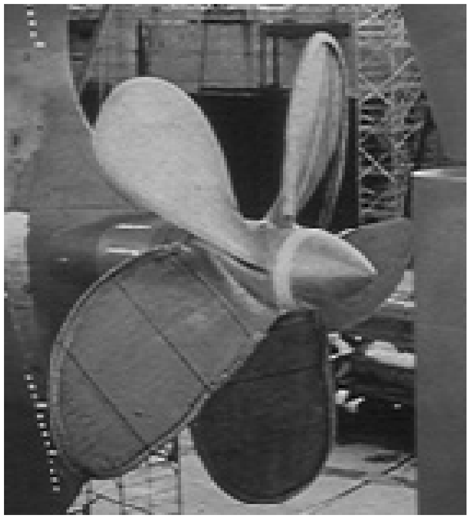

Figure 4. Five Bladed Fixed Pitch Propeller From [5]

Though the propeller has its advantages for its simplicity and durability, since it is a single solid piece, it does have its disadvantages. Because the propeller cannot be adjusted in any way, the only way to control it is by the rotational speed of the shaft. This creates limitation for diesel driven ships since it requires the engines to perform at varying speeds.

2. Controllable Pitch Propeller

The controllable pitch propeller (CPP) is similar to the FPP, with one additional degree of freedom wherein it has the ability to change the blade pitch [5]. The propeller blades can be rotated fore or aft to reduce drag and find the optimum settings without having to reduce the shaft speed, whether accelerating or decelerating (see Figure 5). This allows for better efficiency compared to the FPP.

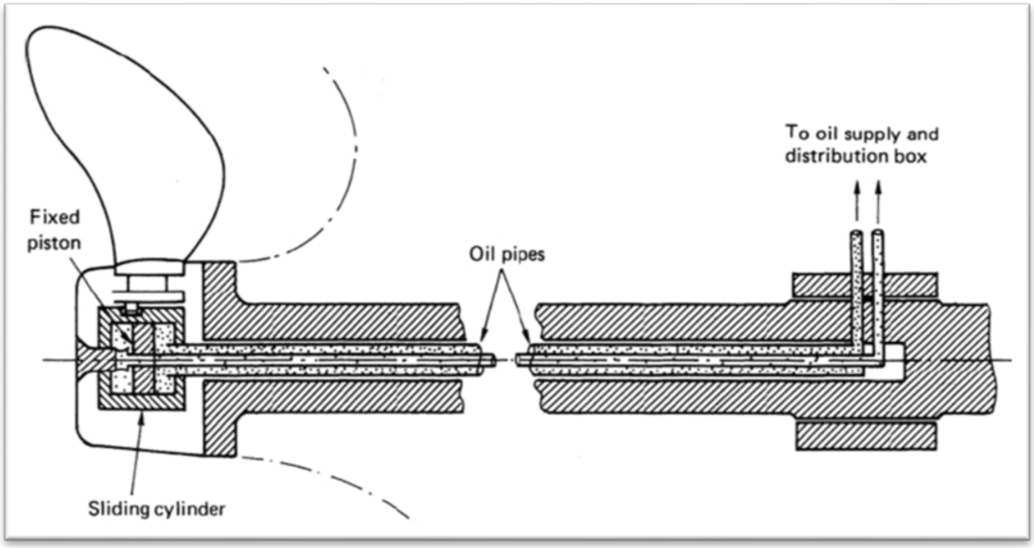

Figure 5. Hub Piston Controllable Pitch Propeller From [5]

Some of the limitations that come from the CPP relate to the complexity of the system. The CPP requires more moving parts, whether driven hydraulically or mechanically, leading for potential of failure in parts. When the propeller comes in contact with ice, the potential for failure is much higher. Since the propulsion of the ship is vital, this could be crucial when there is a breakdown.

C. SETUP OF AZIMUTH PROPULSION PROPELLERS

With the new podded propulsion, variations can be made to a new ship design where varying implementation can be made to come up with differing arrangements.

1. Pusher / Puller (Tractor) Type

The most common propeller setup is the pusher type. This setup used as thrusters allows the vessel to thrust the ship in the opposite direction, similar to a conventional vessel with propeller and shaft. When used in ice breaking situations, it is ideal since it’s least likely to come in contact with ice.

For the puller (tractor) type, the propeller allows water to be pulled through. This improves the inflow of water to provide thrust, since no shafts or underwater appendages really get in the way to create disturbance [5]. Even though the propeller will encounter

ice first, unlike the pusher type, the notion in the propeller will either mill the ice or push it away. The difference of flow of water between pusher and puller type is provided in Figure 6.

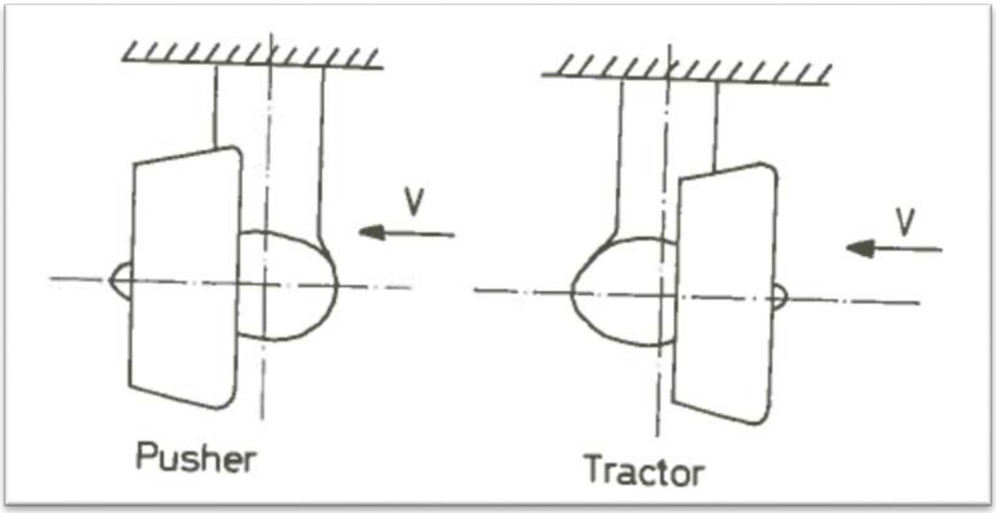

Figure 6. Pusher/Puller Type From [5]

2. Contra-Rotating

Combining the puller type concept and the traditional shaft driven propeller, is the contra-rotating propeller (CRP) setup. Two propellers positioned behind one another, rotating in opposite directions, sitting coaxially (see Figure 7). The CRP allows the hydrodynamic advantage of regaining lost rotational energy from the first propeller, which is the conventional single screw system. The second propeller is of the puller type with an additional propeller blade from the first propeller, to help reuse the wash from the first propeller. The aft pod has been known to create disturbances when rotated in a direction away from being coaxial. Though the concept has been used in airplanes and torpedoes, little testing has been conducted on its use in ice breaking or navigation for ships [5].

Figure 7. Contra Rotating Propeller From [5]

D. VARIATION OF AZIMUTH PROPULSION

1. Nozzle or Ducted

As the name indicates, the propulsion setup has ducting that encompasses the propeller. This allows for the flow to be concentrated to the propeller as well as protect the propellers from obstructions such as large chucks of ice. The ducting is sometimes labeled as a nozzle, but makes no different since two components determine the type of ducting or nozzle. The shape of the ducting as well as the propeller type determines the effect or characteristic the ship requires for thrust. The two most common types are accelerating and decelerating ducts. Accelerating has great performance in forward operation but poor backwards operation, since it speeds flow through and accelerates it past the propellers. Decelerating duct slows the flow and allows for greatly reduced cavitation and underwater noise control. Whether which type of ducting a vessel may have, the shortfalls are that the ducting contributes to the ships drag. But the greater concern is in cases where broken ice pieces get sucked into the duct and impact the propeller. Not only does close proximity of the ice block influence the flow of water but can potentially damage the thin blades which are meant for performance [6]. Not only

will the propeller blade have damage, but the ice piece not milled can bounce inside the ducting causing damages to the ducting profile which degrades performance as well.

2. Motor Location

Another minor modification to the propulsion system is deciding on the location of the motor that drives the propeller. Both cases allows for 360 degree rotation and thrust in any direction. Azimuth propulsion began with the propeller driven mechanically, having motors located just above the propeller and mechanically driven with shafts and gears. Later modifications came about where the motor was actually located inside of a pod, hence the name podded propulsion (see Figure 8). This allowed less likelihood of mechanical failures of bearings or misalignment. But having a motor inside a pod brings limitation to maintenance or repairs when issues come about.

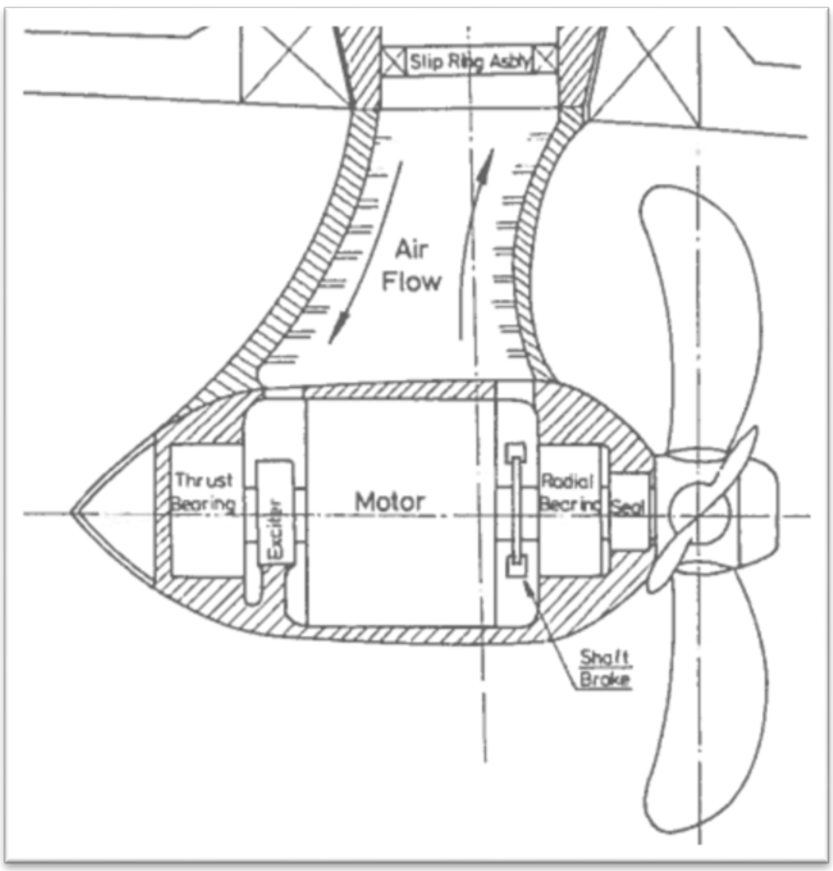

Figure 8. Motor Inside Pod From [5]

E. COMBINATION OF CONCEPTS

1. Double Acting Concept

The double acting concept came about by reviewing vessels that have hulls designed to navigate through or break ice. Traditional ships operating in ice have poor qualities for transiting in open waters due to the shape of the bow. With that in mind, the concept came up for a vessel to be able to transit in open waters, but break ice going astern (see Figure 9). By using the podded propulsion with a fixed blade puller type propeller, the double acting concept was created. This allowed for ships to have optimized hull forms for all conditions, improved maneuverability in ice and economical beneficial [7]. The concept has not been transferred over to vessels smaller than a tanker but has potential to lead to new paths for future ice-breaking vessels.

Figure 9. Double Acting Concept From [7]

2. Multi-Propulsion Arrangement

A step further in the revolution of ice breaking saw the emergences of the oblique ice breaker. Icebreaking tankers or ice breakers have limited capabilities in breaking ice in canals or in restricted channels. With a three podded propulsion setup on the ship, the oblique ice breaker can break ice with not just bow and stern but break and push ice with its side hull (see Figure 10). The vessel allows channels to be opened up twice as wide compared to what a tanker or ice breaker can create. This unconventional ship concept stems from the technology of podded propulsion [8].

Figure 10. Oblique (Three Podded) Ice Breaker From [8]

III. MODELING AND ANALYSIS

A. SETTING UP THE MODEL

When designing the model propeller and block of ice, the two objects were developed through a 3-D mechanical computer-aided design (CAD) program that is widely used in academic institutions and in the industry. Creating the ice block was simple, just designed a simple rectangular block based on the selected dimensions. Designing the propeller was much more complex. The shape, the pitch, the rake and skew, the thickness and length all have to be taken into consideration. Instead of spending countless hours attempting to come up with the precise curvature and outline for a single propeller blade, a tool created by a team of researchers from Massachusetts Institute of Technology (MIT) was used to help design the propeller [9].

The program is called OPENPROP, which is used for design, analysis and fabrication of optimized propellers or horizontal-axis turbines. The numerical modeling is based off of parametric design codes used by the USN and commercial designers. OPENPROP is written in MATLAB M-code and a "user-friendly tool that can be used by both propeller design professionals as well as novices to propeller design" [9].

With the codes for OPENPROP implemented in MATLAB, use of the program to design a propeller model was not difficult. By running the MATLAB codes, a simple and basic four-bladed propeller model was designed in MATLAB. As shown in Figure 11, the model has a basic hub used for its individual blades and is shown in an isometric view.

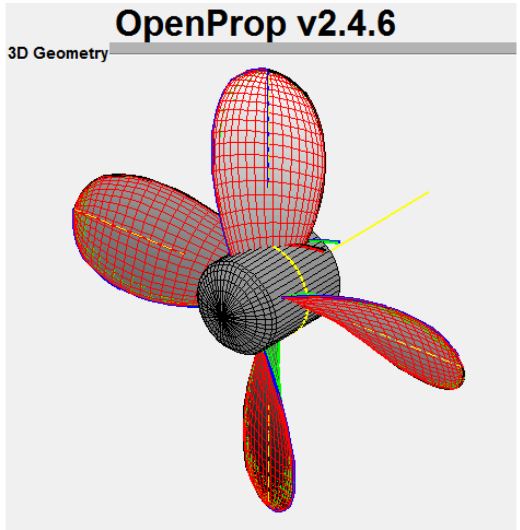

Figure 11. OPENPROP in MATLAB

The program allows for the 3-D graphical propeller design created in MATLAB to be exported to CAD programs such as Rhino or SolidWorks. When the design is transferred into SolidWorks, the original propeller blades profile is divided into multiple contours, or airfoils, from the tip to the root. Only a single propeller blade is transferred, rather than the entire propeller produced in OPENPROP. By combining the contours of the single propeller blade in SolidWorks as depicted in Figure 12, one can produce a single solid object which in turn will become a single propeller blade upon meshing of the solid.

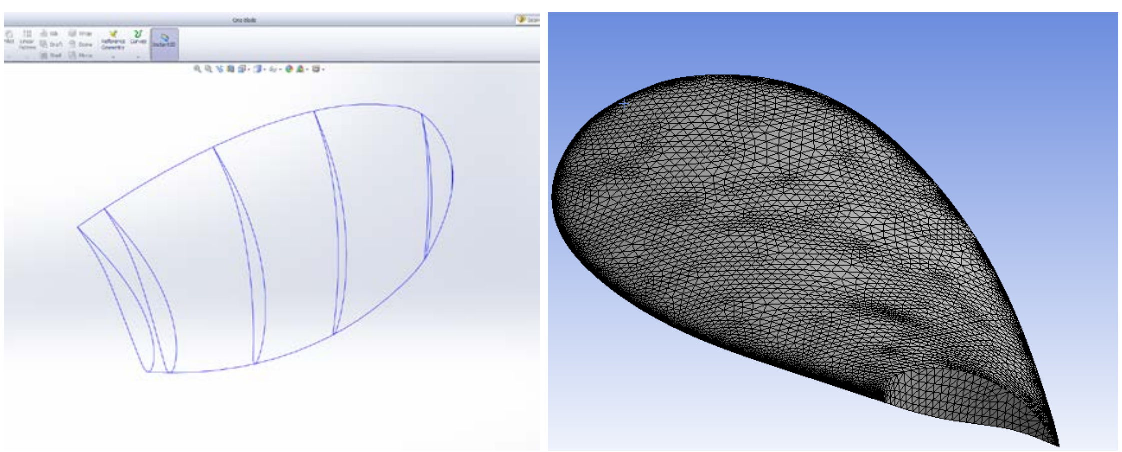

Figure 12. Single Propeller Blade

With the single propeller blade created, all that's required is a hub. The hub was designed in a simple fashion, a cylinder that's slightly drafted towards the nose of a cone. The single propeller was attached to the hub and reiterated in a circular pattern around the hub to create a four bladed propeller as provided in Figure 13.

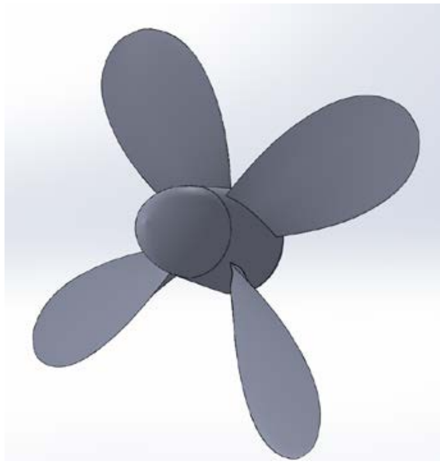

Figure 13. Final Propeller Design

B. MATERIAL SELECTION

After the model was designed in SolidWorks, the two objects were transferred over to ANSYS. In ANSYS, material selection is required to get an accurate representation of a ship propeller banging an ice block. For the propeller, we chose a stainless steel with the properties of density at 7750 kg/m^3, Young's modulus of 1.93E11 Pa, Poisson's ratio of 0.31 and yield strength of 2.1E8 Pa.

More common materials used for marine propellers are copper based, particularly bronze or high-tensile brass, propellers. Though the bronze based propellers have great strength and corrosion resistance, they are not as strong compared to the stainless steel. Stainless steel is more prone to brittle fracture and severe damage to the propeller can quickly disable the ship. However, bronze propellers will distort and bend, still allowing operation of the ship. Though, for this research, we are looking into propeller impacting with ice, so I chose as stainless steel as the propeller material.

For the ice block, we chose more generalized numbers for the material properties. Since, the property of ice can be varying, pending the density, the salinity of the ocean, the water or air temperature and the thickness of ice which is determined by if it's the first year or multi-year ice. All these factors have studied and researched while no final conclusion can be drawn on how to determine sea ice and its physical properties. Therefore, we averaged values found in studies and used the properties of sea ice found in the Arctic. They created into ANSYS material data for the ice block as having the density of 915 kg/m^3, Young's modulus of 2E9 Pa, Poisson's ratio of 0.295 and kept it as elastic analysis [10].

C. MESHING

Proper mesh is required to solve the simulation using Explicit Dynamic solver in ANSYS. Since the propeller in our model is a solid 3-D object which has a very unique profile, we chose to go with tetrahedron shaped elements to properly mesh the propeller (see Figure 14). The propeller resulted with 10,744 nodes and 23,597 elements when using tetrahedron shaped elements. The mesh could have been refined more to improve efficiency and accuracy of results but trying to over magnify the accuracy can lead to never-ending solution analysis or overshooting the result [11].

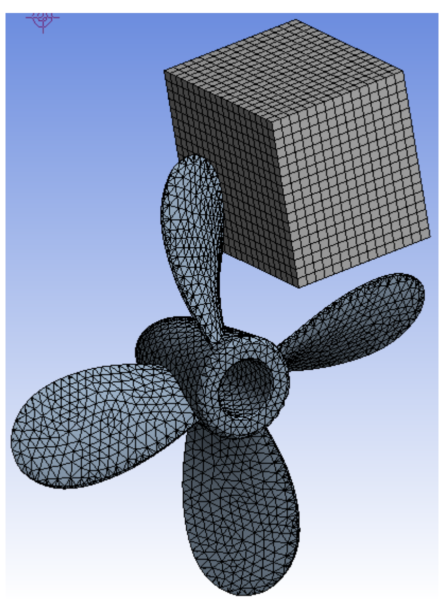

Figure 14. Mesh of Propeller and Ice Block

D. BOUNDARY CONDITIONS

By using the Explicit Dynamics solver in ANSYS, we were able to emphasize the instant the propeller blade and ice block make contact. Prior to using Explicit Dynamics, the ANSYS solver Static Structural was used to set the boundary conditions. The propeller was fixed on the X-axis but allowed to rotate on the same axis as show in Figure 15.

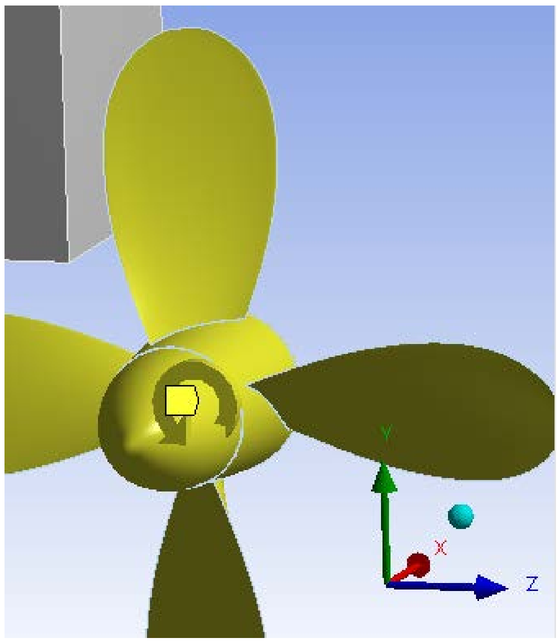

Figure 15. Fixed and Rotating on the X-Axis

The next step was to transfer that data to Explicit Dynamics. We began with the basics to see how the simulation model would react with basic conditions/criteria. Our focus was on the instant the propeller and ice block made contact, so we began with having either the ice move and hit the blade or the blade travel and hit the ice. We found out quickly that without the proper settings, material conditions and boundary conditions, the results were not very plausible. Ice block completely destroying a solid propeller or the propeller blowing up the ice block did not seem realistic (see Figure 16).

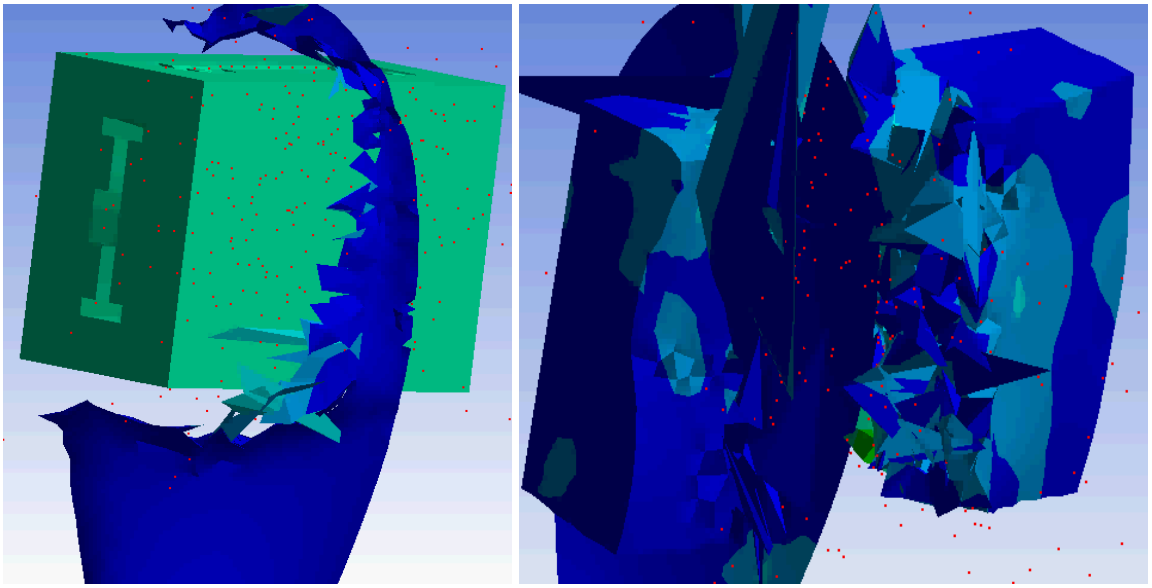

Figure 16. Unrealistic Propeller Ice Block Interaction

After adjusting material properties and arranging proper boundary conditions, we were able to achieve outcomes that made sense. Once the propeller blade and ice responded to impact accordingly, we advanced to giving the propeller angular velocity. We added a small velocity for the ice block to imitate the flow of current or any other source that would give the ice block momentum. Once we identified all the errors for using Explicit Dynamics, we moved on into our parametric studies.

IV. ICE IMPACT RESULTS

A. BLADE IMPACT FROM AXIAL DIRECTIONS

For our initial parametric study, we began with having the ice block flow in from one axial direction (see Figure 17). The propeller would only rotate and not translate. This was to replicate a scenario in case a ship was stuck in ice. The ice would only travel in a single component axis and collide with the propeller rotating at 100 RPM. Each condition was carefully viewed to see if at what instant the propeller made impact and when the ice block bounced away after the collision.

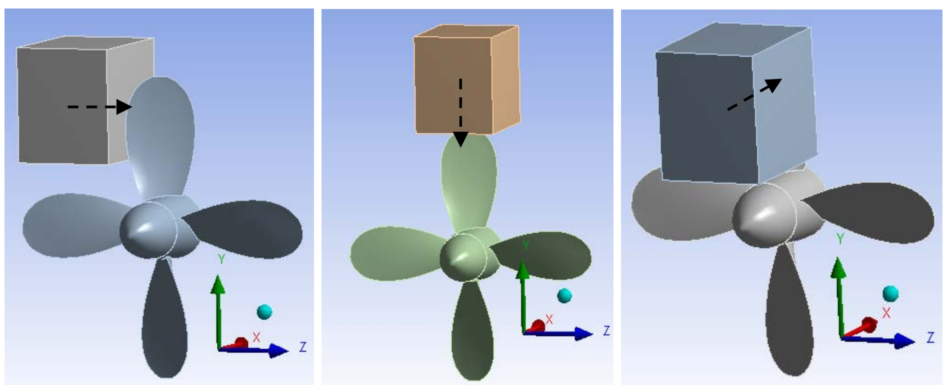

Figure 17. Ice Block Flow in Z-Axis, Y-Axis, X-Axis

The stress propagation of the propeller blade affected by the ice impact and vice versa was examined for all three cases. From reviewing the max stress concentration for the propeller blade, the ice block in the flow of the Y-axis gave the greatest stress at 109 MPA. The ice block felt the greatest stress when flowing in the X-axis at 9.34 MPA. This indicated that the propeller rotating into the ice directly was ideal in breaking or milling ice, while avoiding situations where the ice directly flows onto the tip of the propeller, which is very unlikely since the hull shape or a nozzle can prevent this situation. From here, we wanted to vary the speed of the propeller to see if they affect the stress levels of the ice block or propeller as shown later.

B. IMPACT ON VARIOUS LOCATION ON PROPELLER

Our next study proceeded to see impacts of the ice on different locations of the propeller blade. For the Y-axis, this was not feasible since the ice block traveling down into the propeller blade tip from above could not be determined into three different regions. For the Z-axis and X-axis, the propeller blade impact positions were designated as locations one, two and three as seen in Figure 18. Location one was a region closer to the root of the blade. Location two was the mid-section of the blade. Location three was closer to the tip of the blade.

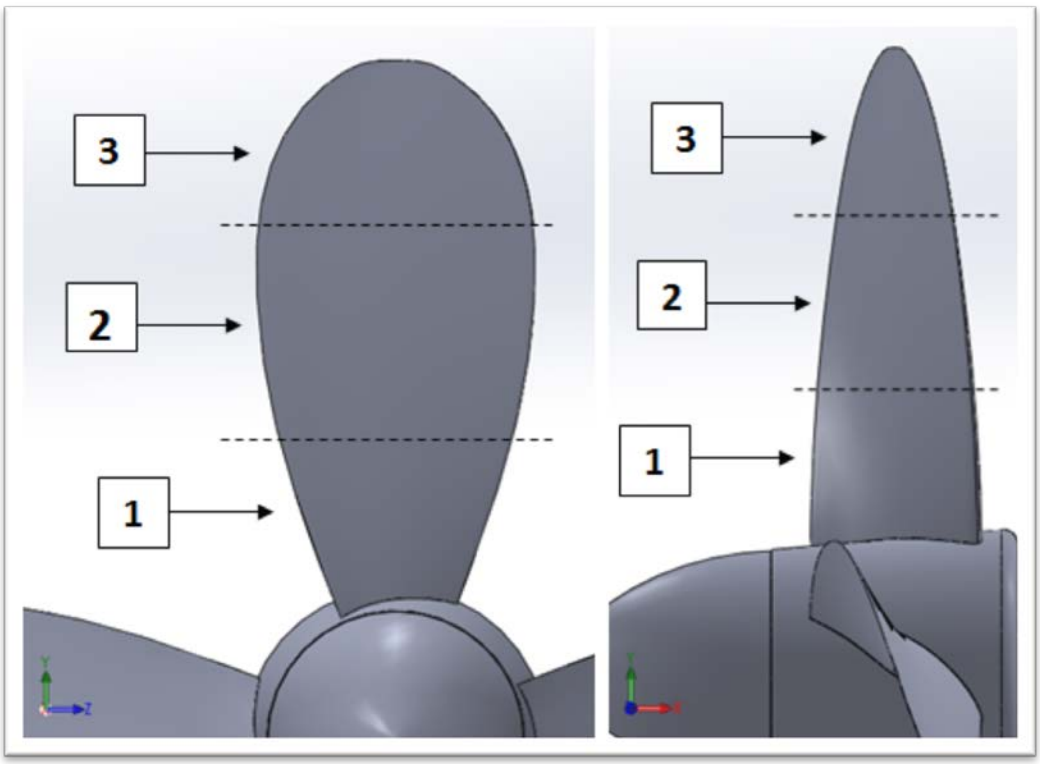

Figure 18. Three Different Impact Locations for Ice Flow in Z-Axis and X-Axis

The rotational velocity of the propeller was maintained at 100 RPM and the ice blocks velocity was the same 0.5 m/s. Interestingly enough, the location of impact the ice had on the propeller blade provided noteworthy results.

The impact of the ice in mid-section along the Z-axis, location two, provided data as to be most detrimental to the propeller blade (see Figure 19). At impact location 2, the propeller blade felt the greatest stress while the ice felt the least amount of stress (see Figure 20). While near the tip of the blade, location three, the propeller felt the least amount of force compared to the others while the ice felt a low force as well. This can be due to the fact that the propeller edge carves the outer edge of the rectangular ice block and there is the least amount of contact. The root, or base, of the blade received an average between the two locations, but a noteworthy find is that the base of the blade delivered the greatest stress to the ice upon impact. If the propeller would be milling ice, the ice impacting around the root of the blade would be the ideal predicament and would have the least impact on performance and longevity of the propeller.

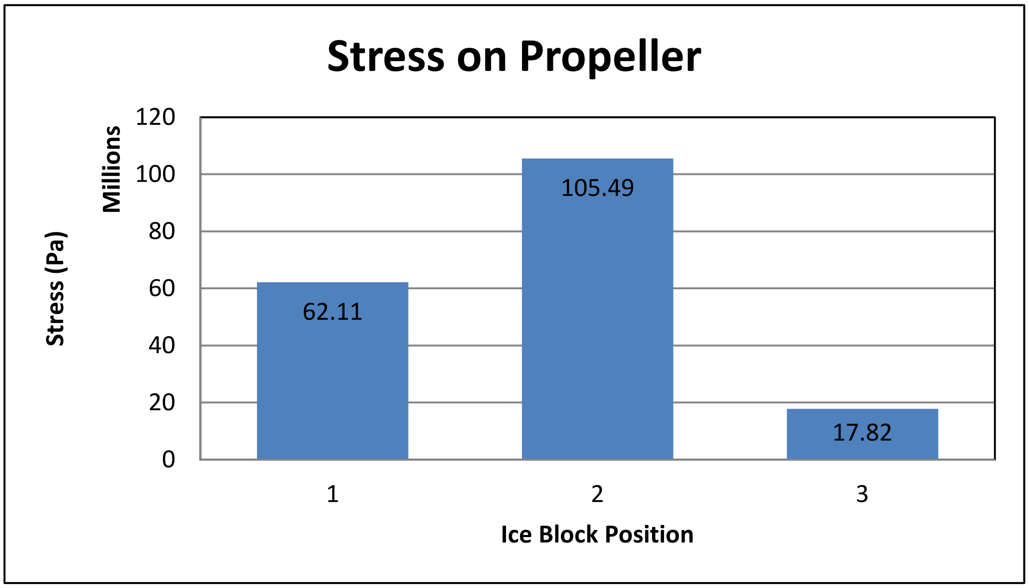

Figure 19. Locations of Impact on Propeller in Z-Axis

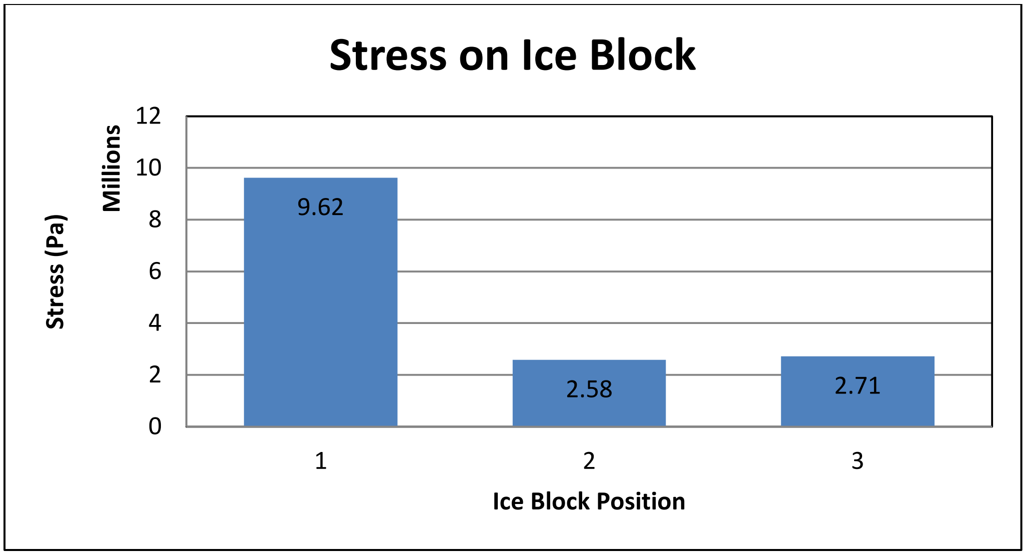

Figure 20. Locations of Impact on Ice in Z-Axis

Impacts of ice in the X-axis proved to have similar results as the Z-axis for the ice block. When comparing the results for the propeller, results showed that the propeller sustained less stress in the X-axis than in the Z-axis. The results showed that location two of the propeller in X-axis acquired the most stress with its value less than 50 percent of the location two in the Z-axis (see Figure 21). Just as the Z-axis had the most damage to the ice when impacted in location one, the results held true for location one in the X-axis (see Figure 22). Since, in this case, the stress felt by the ice was greatest for location one, the ideal case would be having the ice block collide near the base of the propeller.

One noticeable result found in the X-axis ice impact was for location three. All the other results showed that the max stress occurred at the location of the impact (see Appendix A). For location three in the X-axis, the max stress occurred in two locations. Figure 23 shows the max stress occurring just below the impact point on the propeller blade as well as near the blade and hub meet. The max stress value on the propeller may not stand out, but the fact that the stress propagates down near the base of the propeller offers concerns on the base of the propeller. The strength and durability around the hub might be an area to pay attention. Looking through these results, it seems vital that the thickness of the propeller blade is important in the strength needed to sustain the impact from the ice blocks. By increasing the thickness near the areas of concern, while

minimizing hydrodynamic efficiency loss, the propellers could increase their strength and durability to avoid life threatening damages to the ship [3].

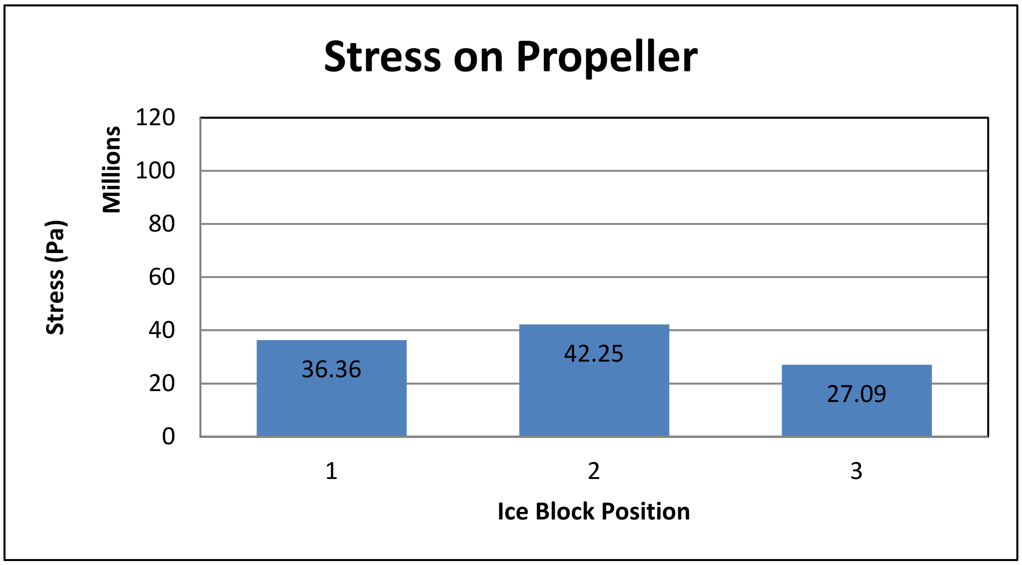

Figure 21. Locations of Impact on Propeller in X-Axis

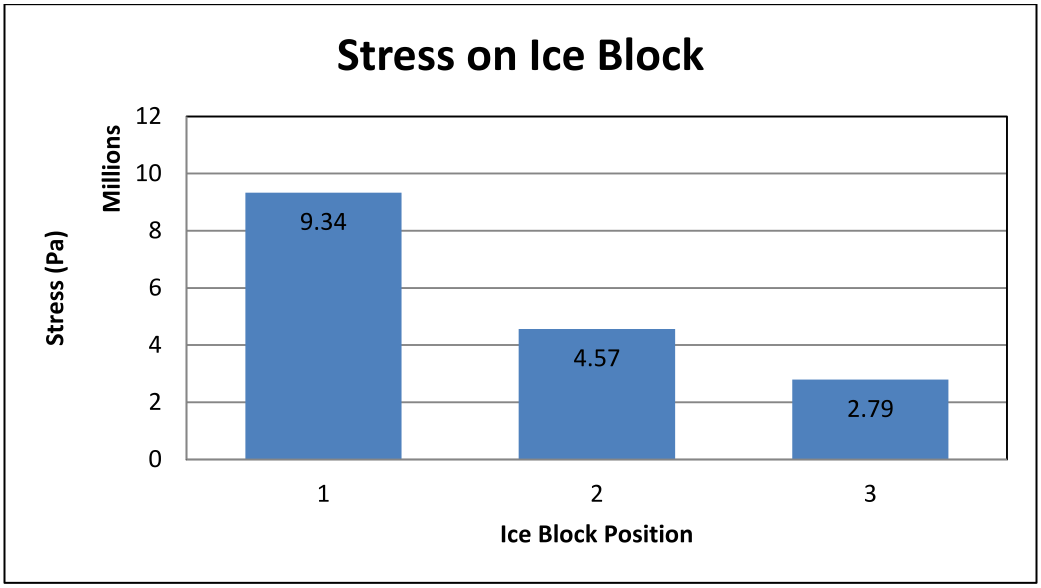

Figure 22. Locations of Impact on Ice in X-Axis

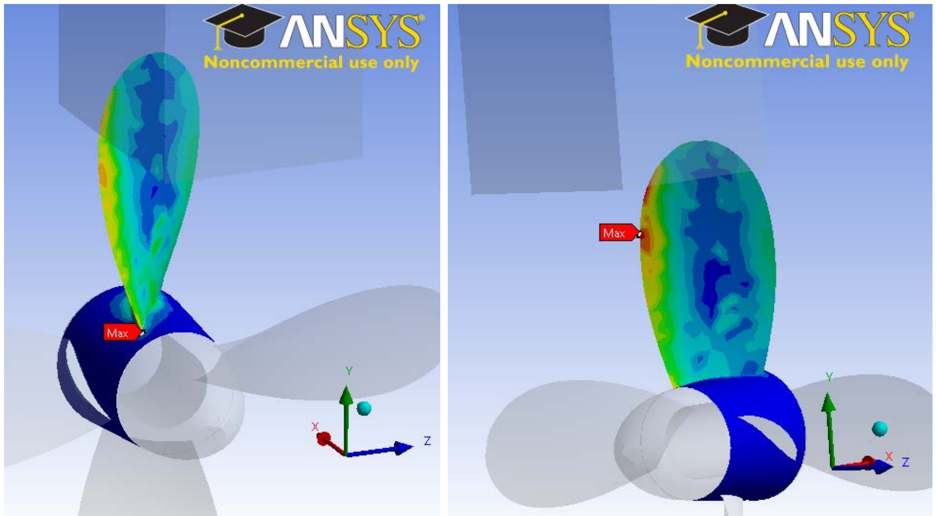

Figure 23. Max Stress on the Base and Edge of Propeller Blade in X-Axis

C. VARYING ICE SPEED

The next case in the parametric study was to vary the speed of the ice block traveling and colliding with the propeller. This time, the ice block would hit the same location of the propeller for all the trial cases, but the speed of the ice traveling to hit the propeller would vary. The ice blocks velocity started from zero to 2.5 m/s or zero to 4.86 knots, while the propellers angular velocity remained around the X-axis at 100 RPM.

For the ice impacting the propeller, an expectation was that as one increased the speed, the stress onto the propeller after impact would increase. The results gathered showed our expectations were flawed, (see Figure 24). The stress level on the propeller and ice would increase constantly but eventually change its slope after reaching some point between two and four knots depending on the impact direction. The stress on the propeller seems to gradually level off as the speed of the ice increases. The Z-axis is the only direction where the propeller would make contact with the ice when the ice block had zero velocity since the propeller blade rotated into the ice block. That is why the plot starts off at a small stress compared to the other two directions.

When varying the ice speed in the Y-axis, the propeller felt the greatest max stress value compared to the Z and X-axis. At zero knots, the propeller rotating by itself could not hit the ice so no stress value was gathered as the first data point. Interestingly, the

stress felt by the propeller quickly increased as the speed of the ice grew. The stress felt by the propeller in the Y-axis was greater than 100 MPa compared to the stress for the Z and X-axis! All of the max stress in the Y-axis occurred at the point where the ice block and propeller made contact (see Figure 25). This data showed that the ice block colliding into the blade tip of a propeller is of significant concern. A ship should try to avoid any scenarios where the blade tip of the propeller impacts directly onto a block of ice.

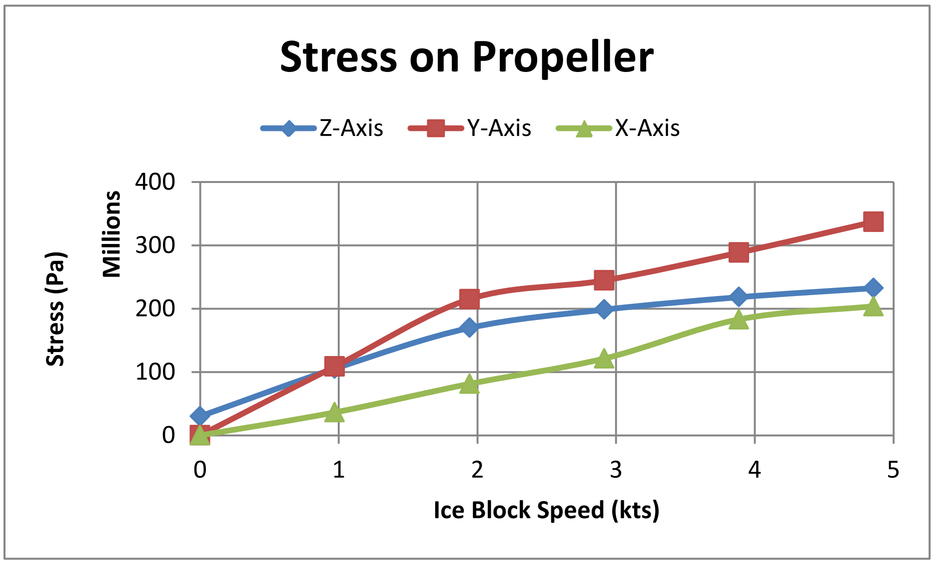

Figure 24. Stress on the Propeller by Varying Speed of Ice

A noticeable interval in the plot shown in Figure 24 is the time between two and three knots for the Z and Y-axis. For the Z-axis, it seems to be the point where the propeller begins to plateau on the stress it experiences from the impact. However, for the Y-axis, plot resembles something of an inflection point. This simulation for this specific case was ran twice to verify the results and data. After coming across this result, to validate the reasoning behind the inflection point, further investigation will be required to substantiate an answer.

As brought up on the previous two impact directions, there is an interesting interval that the X-axis showed. Instead of the interval for two and three knots for cases in the Z and Y-axis, the X-axis showed an inflection point between three and four knots. Again, the simulation for verified with two additional trials. Further exploration in the

reasoning behind the inflection point will need to be examined. Running simulations, focused on the ice block speed in the interval of two and three knots might be able to better explain the plot. Also, possibly exploring further into the propeller profile can provide further explanation.

Out of the three axis ice impact, the X-axis impact allowed for the ice block to feel the greatest amount of stress. As seen in Figure 26, the stress constantly increased with the speed of the ice block. In the direction of Z and Y-axis, the stress to the ice block did not show much significant change compared to the X-axis. This lead to an early assessment, that milling ice head on or in the X-axis, may be the ideal condition for the propeller.

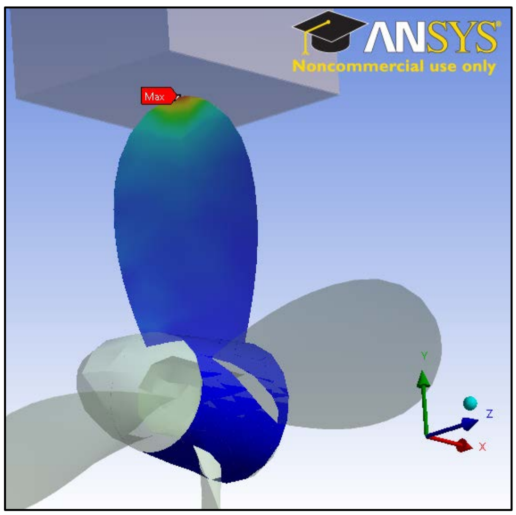

Figure 25. Location of Max Stress on Propeller in Y-Axis

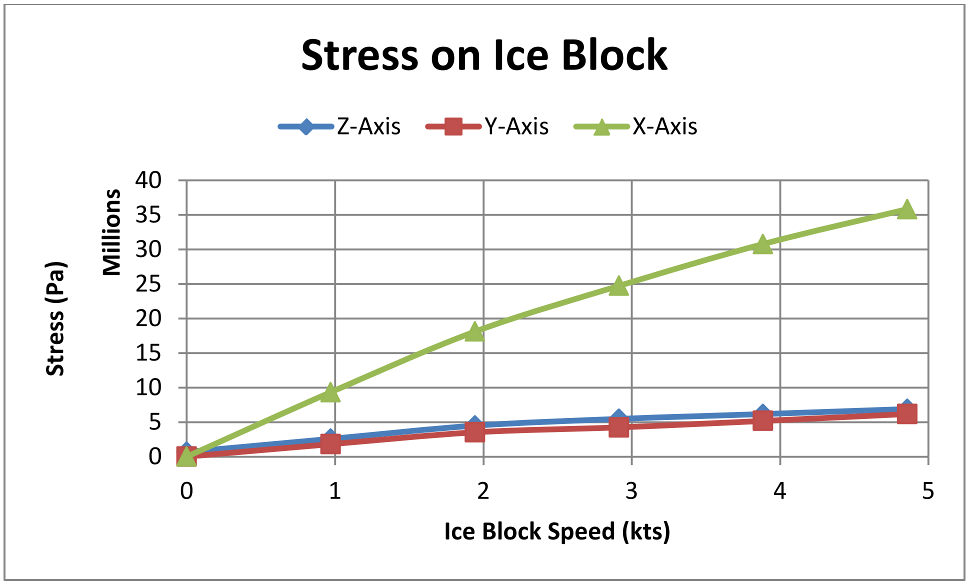

Figure 26. Stress on the Ice Block by Varying Speed of Ice

D. VARYING PROPELLER ROTATION

The next parametric case was to vary the angular velocity of the propeller. In the previous case, we varied the ice speed and the propeller rotation was kept at 100 RPM. For this case, we maintained the ice speed at 0.5 m/s and varied the propellers angular velocity between zero to 150 RPMs. The findings from this case proved to verify an earlier assumption as well as bring up new awareness.

To start off, in the Z-axis, whether one has the ice block traveling at a higher velocity or the propeller rotate at a faster angular velocity, the impact delivers a greater stress on the propeller. Unlike the previous case with the faster ice, the stress on the propeller did not plateau as one increases the angular velocity of the propeller. The propeller stress level continued to rise (see Figure 27). The stress rose in a constant, linear fashion, which did not have an unusual inflection point as in the previous case. Out of the three axial impacts, the Z-axis was the most unfavorable case only when the propeller rotation was at a high angular velocity. From this result, it’s important to regard that the propeller speed should be considered to avoid damages to the propeller.

For the Y-axis, the propeller stress started out as significantly high. Once again, this confirmed that ice impacting the propeller from this axial direction is damaging to

the propeller. Surprisingly, as the rotation of the propeller speed increased, the stress on the propeller began to decrease by a small amount. The rotation speed of the propeller passes by the ice block quicker allowing for less of the ice blocks load to be applied onto the propeller. Still, the rationalization for avoiding the ice striking the tip of the propeller does not change and should continue to be prevented.

The X-axis impact of the ice block to the propeller proved to be ideal and validated the best situation for ice impact. Out of the three axial impacts, the propeller feeling the impact of the ice from the X-axis experienced the least stress as shown in Figure 27. Not only was the stress value the least, the stress onto the propeller did not change as the angular velocity of the propeller was changed. The plot and data seems uninteresting but established the idea that the head on, or X-axis ice impact is the scenario to be sought out.

To add to the case that the X-axis impact is ideal, is the fact that the stress the ice block felt was also the greatest in the same direction (see Figure 28). Stress on the ice block for the axial impacts for Z and Y-axis data showed insignificant data but when comparing to the X-axis, meaningful comparison could be made. The ice felt nearly three times the stress in the X-axis compared to the other axial impacts. Another interesting note is that the stress on the ice did not change as the propeller rotation speed changed. Just as the data for the propeller was constant, so was the plot for the ice in the axial impacts for the X-axis. By collecting these data, the plots demonstrate some of the earlier beliefs of the blade tip being sensitive and head on ice impact being best case scenario.

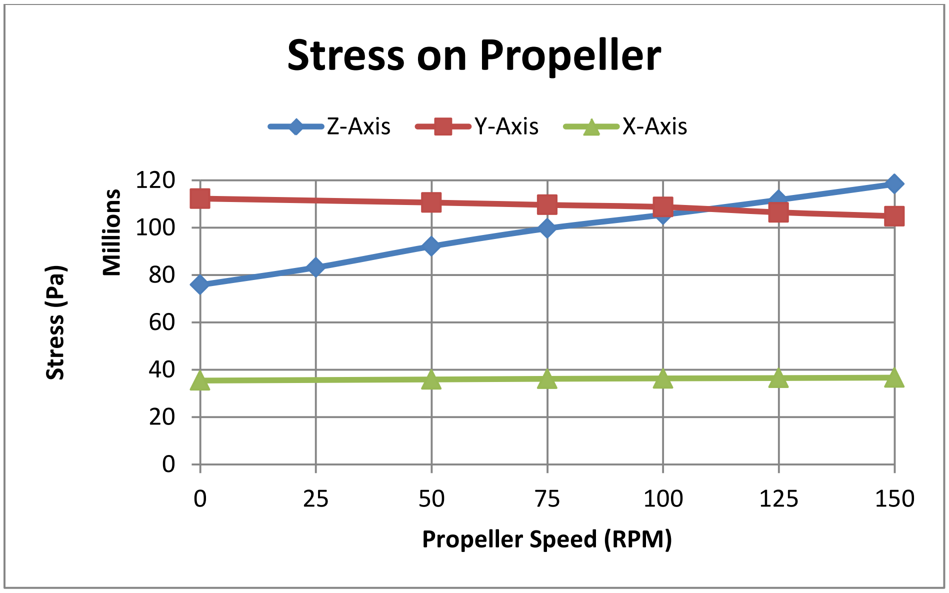

Figure 27. Plot of Varying Propeller Rotation

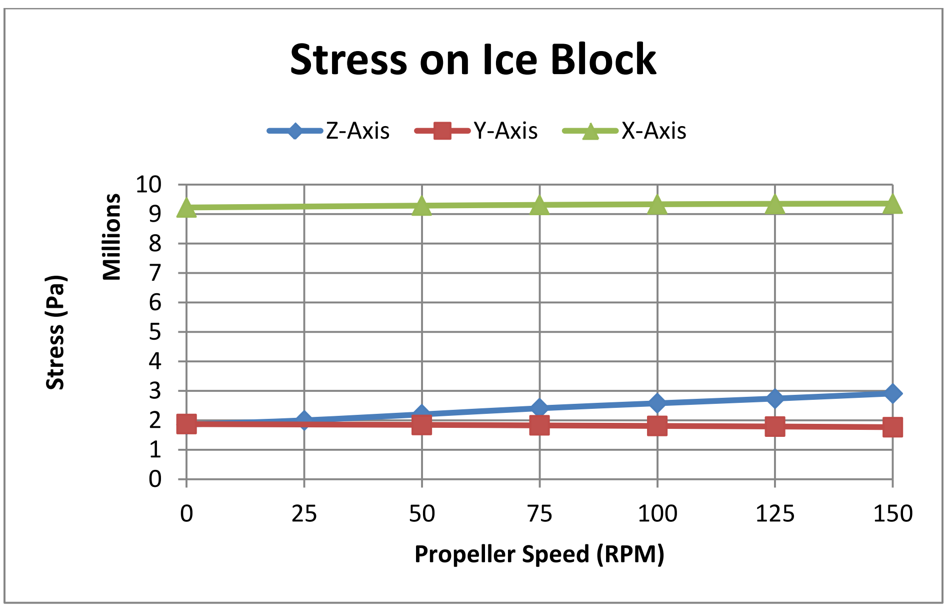

Figure 28. Varying Propeller Rotation on Ice Block

E. TRANSLATION IMPACTS

Moving onto the next case, we decided to allow the propeller to translate along the X-axis. We continued with the ice traveling at 0.5 m/s, the propeller rotating at 125 RPM, while varying the propeller translating at two to five m/s or 3.89–9.71 knots. Instead of keeping the propeller at 100 RPM, we changed it to 125 RPM due to the fact

that most propellers performing under an azimuth or podded propulsor operate within the parameter of 100 to 150 RPM. And by giving the propeller a translation velocity, it provided more of a sense the propeller was traveling alongside as part of a vessel cruising in water with ice. As the varying speed for the propeller in translation, we wanted to imitate a vessels speed that resembles icebreakers or tankers navigating through ice.

The data collected in the directional impact in the Z-axis proved to be an average between the Y and X-axis. The slight increase of stress on the propeller was not of significance and as seen on the plot in Figure 29 it is nearly constant throughout the increasing translation speed. From the previous simulation run with the propellers angular velocity increasing, the translation speed of the propeller with a rotational velocity maintained provided results slightly different than what was expected.

Axial impact on the Y-axis was unexpectedly different from the previous cases. It was not expected for the ice impact on the propeller blade tip to be the lowest stress on the propeller blade when translating. The previous cases showed that the impact on the blade tip to experience the largest stress. After comparing the results with the varying propeller speed, it actually made sense for the results gathered from the Y-axis. Since the propeller is not only rotating away from the ice block but translating away as well, the stress of the propeller becomes less due to the ice block not able to fully impact the propeller.

While translating the propeller, the impression of advancing the propeller as if part of a vessel and an ice impacting the propeller showed to be the most unfavorable. The stress values collected in axial impact for the X-axis proved to be the largest out of the Z and Y-axis (see Figure 29). As well the plot shows constant increase of stress as translation speed rises. With a simple understanding of physics, it makes sense for the X-axis to have the greatest stress. Having two objects crashing into each other head on is going to have the most force than any other situation. And in this case, we speed up the propeller translation directly into the ice block.

When looking at the stress sensed by the ice block, the previous statement is true. A head on contact between two objects is going to provide the greatest blow to each

object. In this case, the X-axis impact stood out by a larger margin, almost 15 times more, compared to the Z and Y-axis impacts (see Figure 30). Though from the previous scenarios of varying the ice speed or the propeller rotation, having the ice impact the propeller from the axial direction in the X-axis was ideal, but in this case it's quite the opposite. The translating propeller setup draws up the idea that one can possible break ice the easiest when directing the propeller head on, but the propeller is going to take a huge toll. This will be a topic debated when designing a ship navigating in waters with ice. Is it better to have a propeller that will sustain the impact from ice but be able to mill or break ice head on or to avoid that all together with a different arrangement? With the concepts of double acting ships or the multi-pod oblique icebreakers, these are topics to discuss very carefully.

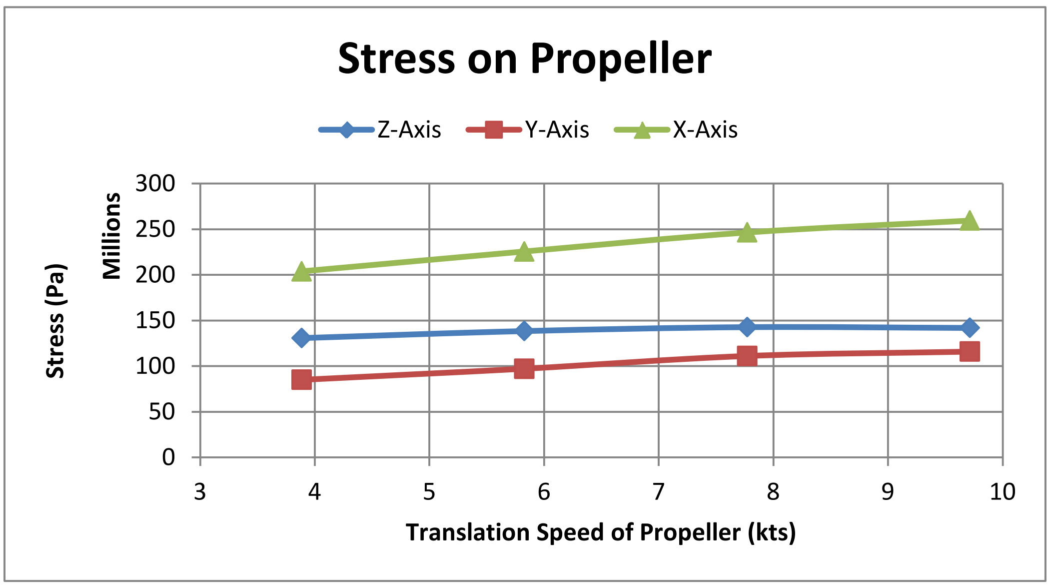

Figure 29. Translation for Propeller on Ice Impact

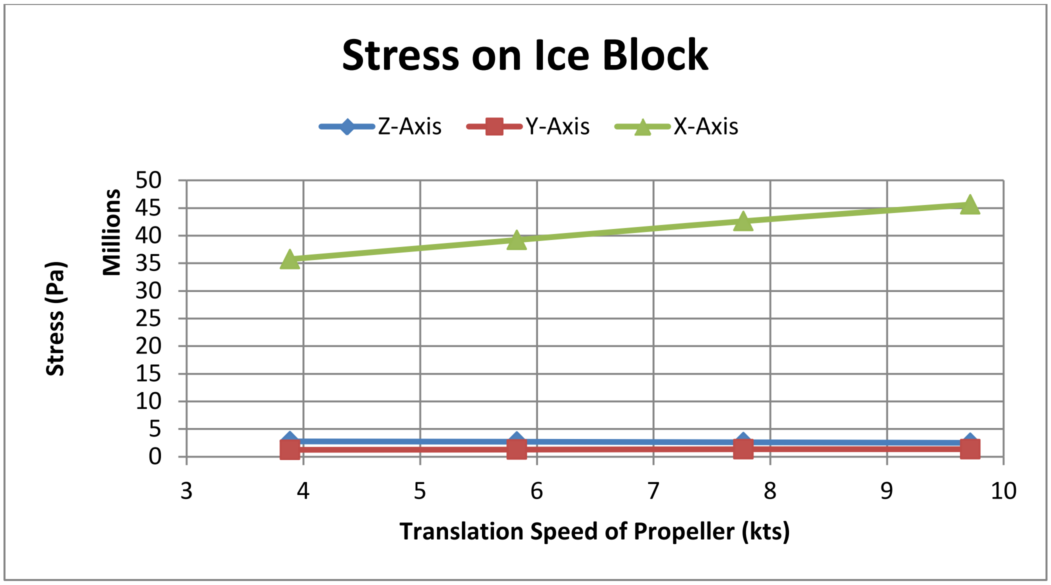

Figure 30. Impact on Ice Block With Translating Propeller

F. VARYING ICE BLOCK SIZE

Throughout the parametric study, we kept the size of the ice block as the same rectangular shape to crash into the propeller. Out in the Arctic, or any ocean with ice, there's varying size of ice. Therefore we changed the size of the ice block making impact to the propeller. We name the size we kept throughout previous cases as normal. Then we had one half the size of the normal ice block as well as twice the size of the normal (see Figure 31). The propellers rotation was held to 100 RPM and the ice blocks speed was kept at 0.5 m/s. The only varying aspect was the size of the ice block.

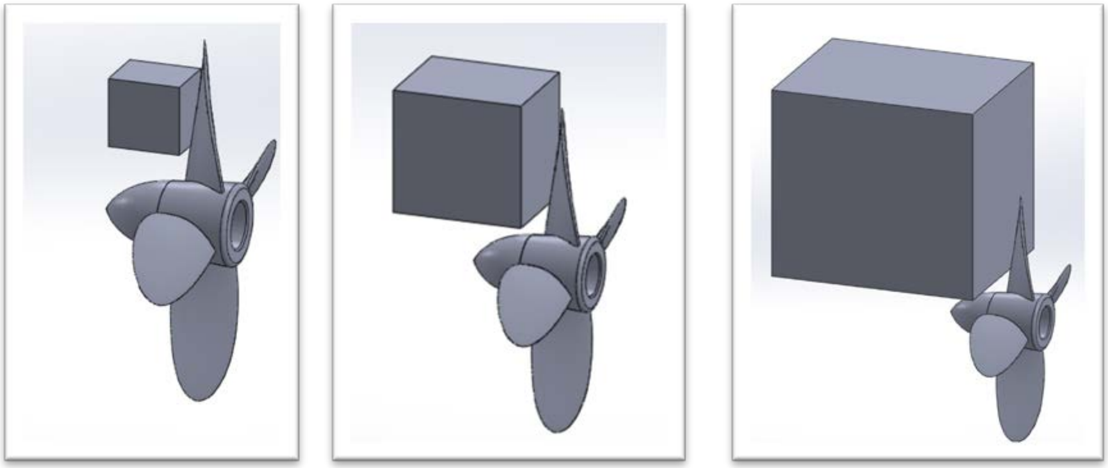

Figure 31. Size of Ice Blocks, Half Size of Normal, Normal, Twice of Normal

The different size ice blocks crashing onto the propeller in the Z-axis provided data that was very interesting. One can expect that as the size of ice get bigger, the greater the stress the ice block can afflict onto the propeller upon collision. However, that was not the results uncovered from running the simulations. As one can see from Figure 32, the plot shows that half of the normal size ice block impacts the propeller less than the normal size, as expected. When looking at the plot when the ice block is twice the size of the normal, the propeller experienced less stress upon impact!

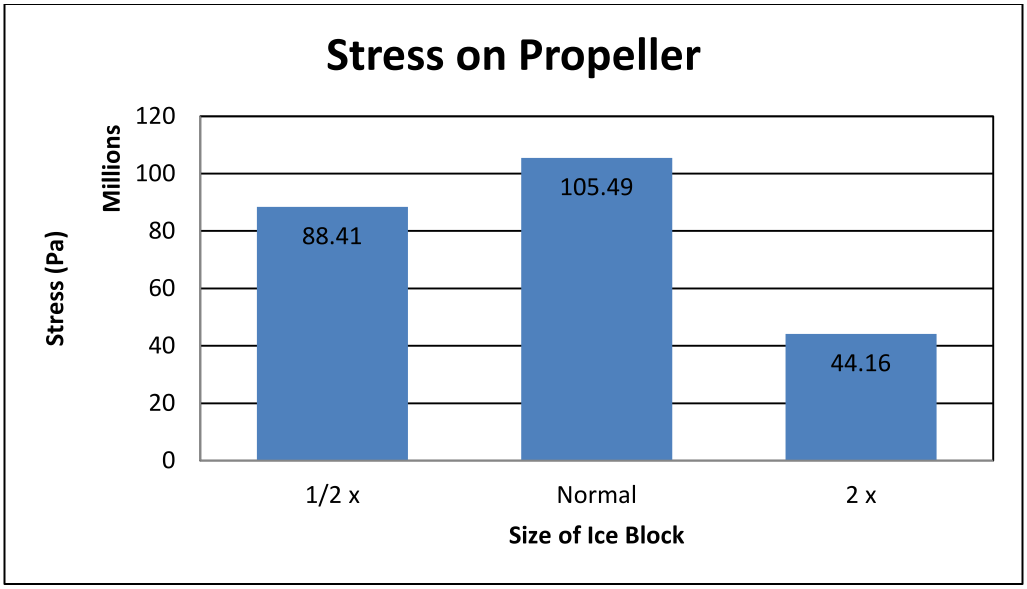

Figure 32. Plot of Varying Size of Ice Block on Propeller in Z-Axis

The result did not seem plausible so the actual simulation was reviewed in ANSYS. A closer inspection provided insight on something not expected. The stress on the propeller was less due to the fact that the ice block upon impact was catching the propeller rotation and spinning the propeller in the opposite direction. The momentum of the ice block was too great to overcome the momentum of the propeller rotation. Another interesting finding was that the max stress that occurred was at the edge of the hub (see Figure 33). Both findings lead to the idea that if the model propeller had a shaft attached to it, the shaft would experience more of the blunt force from the ice than the propeller would. The max stress that occurred on the hub was because there was no shaft. Not having a shaft made result unique. In real life, a propeller could not rotate in the complete opposite direction after impact unless the shaft was sheared and failed!

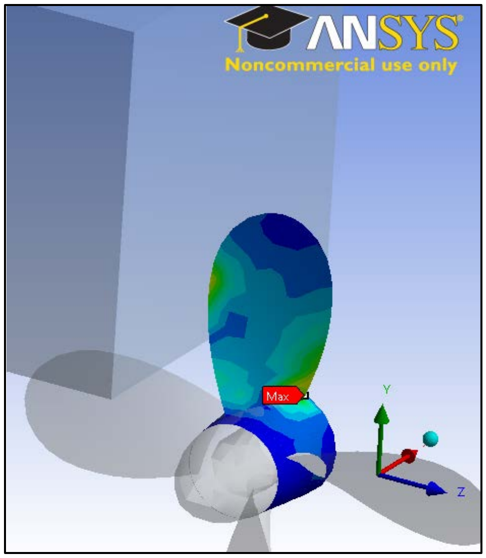

Figure 33. Max Stress on Hub From Large Ice Block in Z-Axis

In the case of varying ice impact in the Y-axis, results did not provide anything special. The original notion of a larger ice block delivering greater stress on the propeller was exactly what happened and was verified. The only vital information gathered was that the propeller experienced the greater max stress when the ice block was twice the size from the normal. The max stress was experienced at the tip of the blade unlike the Z and X-Axis. Seems the propeller blade would go through compression when pressured from the blade tip instead of torsional. The plots can be seen in Appendix A.

Interestingly, the ice impact in the X-axis proved to have similar results as the impact in the Z-axis. The stress the propeller sensed was the lowest compared to the other two axial impacts. Interestingly enough, the half size of normal ice block provided a larger load onto the propeller than the other two sizes (see Figure 34). This is something that will have to be further investigated since the results could not be clearly explained during this research. However, the low stress for the ice block twice the normal size was something that we were able to shed light on.

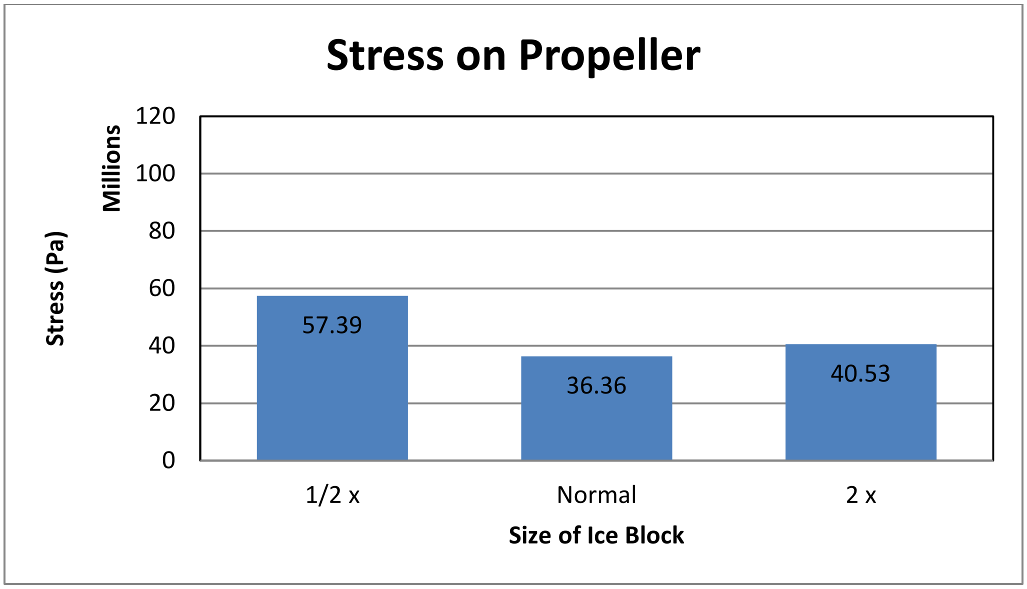

Figure 34. Plot of Varying Size of Ice Block on Propeller in X-Axis

We took a closer look into ANSYS for the X-Axis as well to see why the value was so low for the larger ice block. What was discovered when examining the large ice block in the Z-axis was occurring in a similar fashion to the propeller model in the X-axis. Instead of the propeller being turned into the opposite rotation, the entire propeller was being rotated backwards (see Figure 35). As mentioned explaining the results for the Z-axis, this result was only achievable due to the flaw in the model lacking a shaft. Instead of having a shaft, the model was given boundary conditions to emulate the propeller being driven by a shaft from a motor.

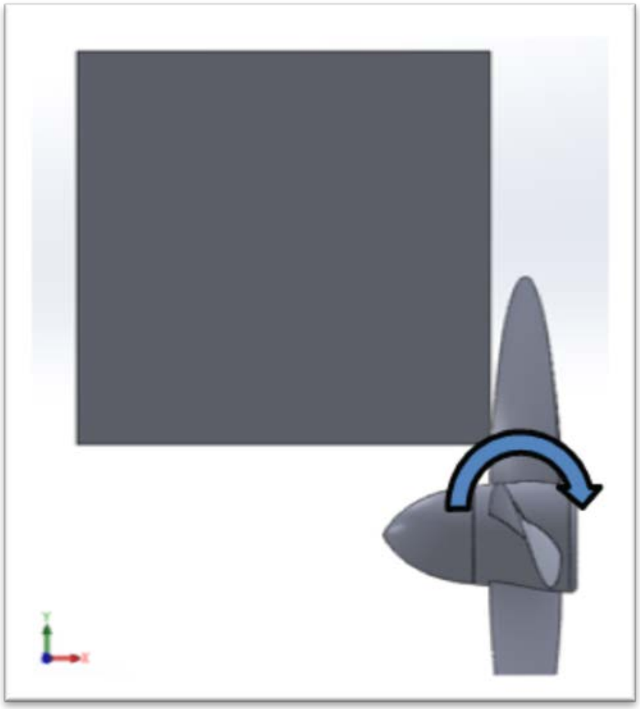

Figure 35. Large Ice Block Rotating Propeller Upon Impact

G. ICE FAILURE MODEL

The last case conducted in the parametric study was to change the ice block into an elastic-plastic condition. In all the previous cases, the ice block was in an elastic analysis. Elastic analysis of an ice block has a limitation since that indicates that the ice block will not break apart when contacted by a blunt force. In reality, ice breaking apart resembles a brittle material failure [10].

Trying to model the ice block to break apart and separate into little pieces can be difficult to model. As a simple and approximate way to represent ice failure, the elastic-plastic analysis was conducted for the ice block. The stress-strain curve for the ice was assumed linear elastic and perfectly plastic. The yield strength of the block of ice can differ depending on the brine, temperature and whether it's first or multi- year. Therefore, using an average value we gave the yield strength of the ice block as 2.45 MPa [12]. For the model to apply the elastic-plastic ice, we applied the new condition to a previous case we used. The propeller in translation was reused for this case, but only in

the ice block impacting the propeller in the Z-axis. As in the translation propeller case, the propeller was given the angular velocity of 125 RPM, the ice block traveling at 0.5 m/s and the propeller translating between two to five m/s. In Figure 36, the two conditions were compared to see distinct differences.

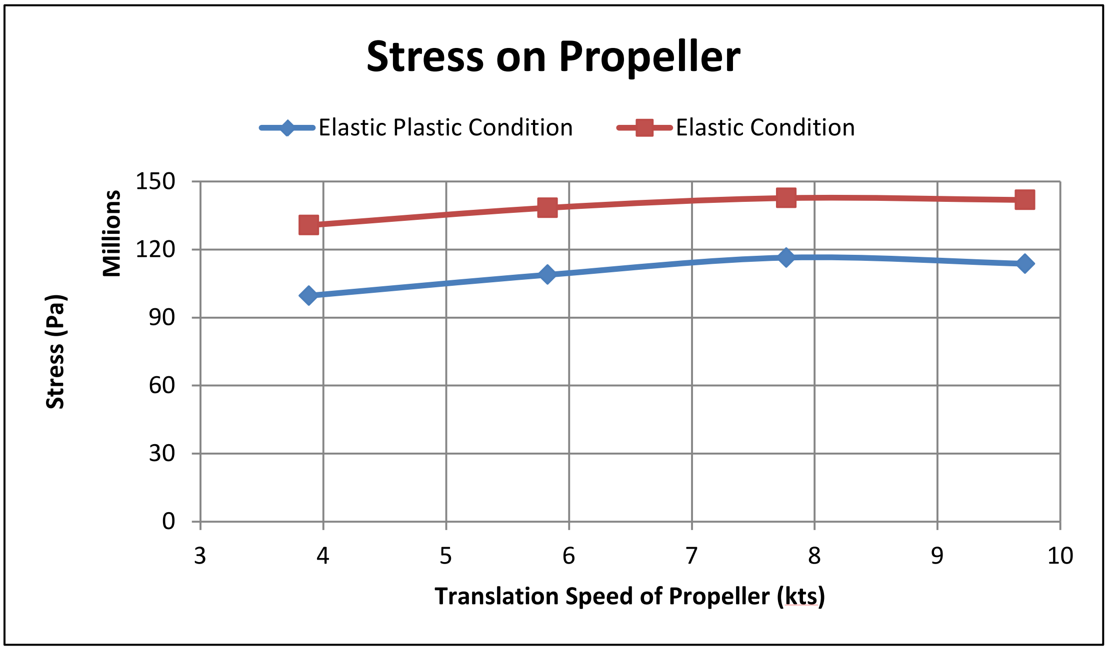

Figure 36. Comparison of Elastic and Elastic Plastic Ice Failure

Just from comparison, one may notice that the elastic-plastic analysis for the ice block delivers less stress to the propeller. Since the ice has a given strength where it will eventually fail, the propeller experiences less stress when the ice block collides with the propeller. When comparing the elastic analysis to the elastic plastic analysis, the elastic-plastic model was 21 percent lower in stress compared to the elastic model! Similarly, the stress the ice felt upon striking the propeller was less as well. The plot can be found in Appendix A. After reviewing and comparing the data, an elastic analysis for the ice block is clearly a conservative approach when trying to model and design a propeller for enduring ice impacts.

V. CONCLUSION

A. DAMAGING AND CAUTIOUS SITUATIONS

Throughout the parametric study, the results and data collected allowed some conclusions to be drawn. For starters, the mid-section of the propeller is prone to experience the greatest stress upon impact of ice. This was demonstrated from the case where the ice block was positioned in three different locations to be crashed onto the propeller. From both the Z and X-axis impacts, location two, impact on the mid-section of propeller, proved to have the greatest stress results. Therefore, this region on a propeller should be designed more robustly to avoid damage due to the collisions a propeller may experience while navigating in icy regions.

Another part of the propeller that proved to be sensitive and easily harmed was the tip of the propeller. In almost all cases, an impact in the Y-axis proved to be very damaging to the propeller. Whether you have a block of ice traveling fast to collide into the propeller or the propeller rotates fast and the ice block collides, both resulted in the Y-axis ice impact to have the greatest max stress at the tip of the propeller. For the ice, minimal stress was felt upon impact, so avoiding ice hitting the tip of the propeller blade is essential. Since the propeller blade tips are essential in hydrodynamic performance, the area needs to either be more robust or protected of ice impacts. Robust blade tips may not help in propeller performance so using nozzles or ducts will need to be investigated closer for future builds in ships enduring ice breaking capabilities.

Initially, the earlier cases proved that the best situation for an ice block crashing into the propeller was head on, or in the X-axis. However, once the propeller was given translation motion, to imitate a moving ship, the axial impact in the X-axis proved to have the greatest stress on the propeller. The propeller rotation speed varying in one place proved to be harmless to the propeller and transferring greater stress onto the ice. But once translation motion is added, the results change and the propeller experiences the greatest stress. One has to recognize and be cognizant that translation and rotation of propeller affects direction of impact. The X-axis impact to a propeller might be

unfavorable, but it does deliver the greater blow to the ice block. A give and take situation in which one has to be sure on the decision the propeller should be arranged in.

B. CONSERVATIVE APPROACH

The final case study wherein the ice block was given elastic-plastic analysis shed some light in the results gathered from this research. The elastic-plastic ice block demonstrated approximately 20 percent less stress to the propeller than did the fully elastic ice block. The conservative approach may be used in future studies and designs. By keeping the ice block in elastic condition, one would be overestimating the impact the propeller would sense. Overestimating will allow researchers and designers to be mindful that the propeller will be more durable and have a longer life cycle if approached in a conservative manner.

C. RECOMMENDATIONS

For future work, there are many concepts that can be altered and improved upon to make the current ice impact model better. To start off, one might apply the concept in a sea water environment. The model used in this research was a basic propeller geometry, with a simple rectangular ice block, colliding into one another in air. If the environment was changed to sea water, the elements of the sea water would presumably have drastic effects onto the model. The hydrodynamic effects the sea water may have on the movement of both the propeller and ice block can provide different results from what was gathered from this research. Adding that single element will allow for the model to become more complex and have more characteristics to be aware of.

Another aspect to help improve on this ice impact model is to add the shafting motor and the casing to the propulsor. In the parametric study for varying ice block size, it was clear that not having a shaft gave unreliable results. The boundary conditions set forth to imitate the shaft did not provide true data to where the damage may occur upon the ice impacts. By adding the shafting, the motor and casing, one can closely examine how the ice impacts affect not just the propeller but other mechanical components. The ice impact may cause torsion on the shaft, or transfer the load from the propeller to the motor, or possibly cause alignment issues where it can damage all components including

the bearings. Improving on the propeller ice block model allows for a more complex model to help examine other components of the propulsor.

Overall, the ice impact model has to become more complex to be more realistic. Giving the ice block the elastic-plastic condition was a start, but the failure has to become more complex. We can make the ice fracture like a brittle material and see if the smaller pieces impact the propeller as well. As one improves upon the model and designs it with complexity, the more reliable the model becomes to use in future research and designing of propellers to be used on ships for ice breaking capabilities.

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APPENDIX A. PARAMETRIC STUDY RESULTS

Data and results gained from the various cases of ice impacting the propeller from either X, Y or Z-axis.

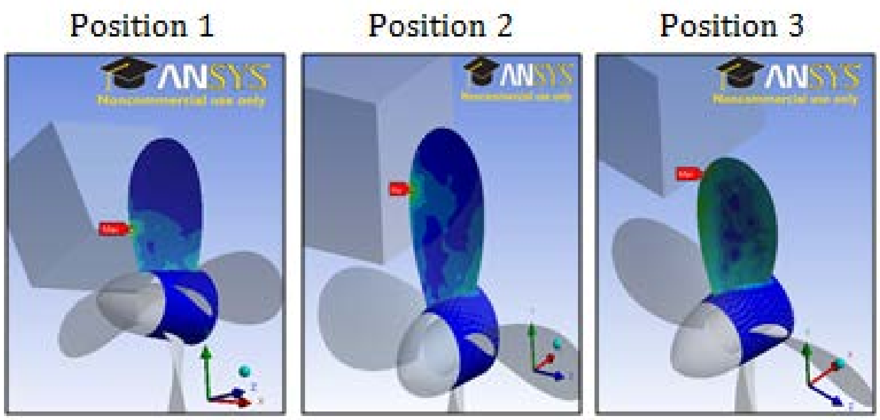

Figure A1. Locations of Max Stress to Propeller upon Impact in Z-Axis

Position	RPM	Stress on Propeller (Pa)	Stress on Ice Block (Pa)
1	100	6.21E+07	9.62E+06
2	100	1.05E+08	2.58E+06
3	100	1.78E+07	2.71E+06

Table A1. Max Stress on Ice Block Position in Z-Axis

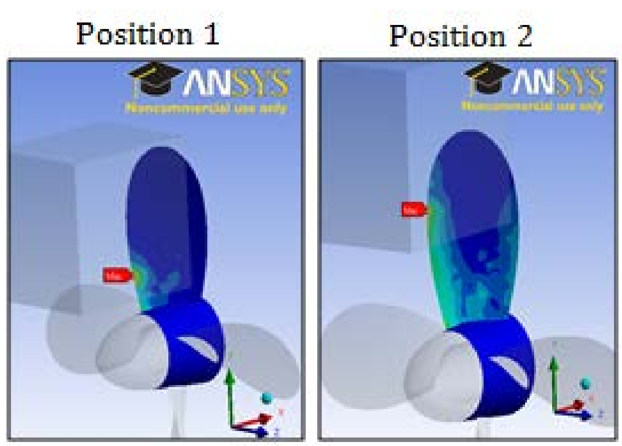

Figure A2. Locations of Max Stress to Propeller upon Impact in X-Axis

Position	RPM	Stress on Propeller (Pa)	Stress on Ice Block (Pa)
1	100	3.64E+07	9.34E+06
2	100	4.23E+07	4.57E+06
3	100	2.71E+07	2.79E+06

Table A2. Locations of Impact in X-Axis

Ice Speed (m/s)	Knots	Stress on Propeller (Pa)	Stress on Ice Block (Pa)
0	0	3.01E+07	6.74E+05
0.5	0.9715	1.05E+08	2.58E+06
1	1.943	1.70E+08	4.49E+06
1.5	2.9145	1.99E+08	5.47E+06
2	3.886	2.18E+08	6.17E+06
2.5	4.8575	2.33E+08	6.89E+06

Table A3. Varying Ice Speed in Z-Axis

Ice Speed (m/s)	Knots	Stress on Propeller (Pa)	Stress on Ice Block (Pa)
0	0	0	0
0.5	0.9715	1.09E+08	1.81E+06
1	1.943	2.15E+08	3.52E+06
1.5	2.9145	2.45E+08	4.24E+06
2	3.886	2.89E+08	5.17E+06
2.5	4.8575	3.37E+08	6.17E+06

Table A4. Varying Ice Speed in Y-Axis

Ice Speed (m/s)	Knots	Stress on Propeller (Pa)	Stress on Ice Block (Pa)
0	0	0	0
0.5	0.9715	3.64E+07	9.34E+06
1	1.943	8.14E+07	1.81E+07
1.5	2.9145	1.21E+08	2.47E+07
2	3.886	1.83E+08	3.08E+07
2.5	4.8575	2.04E+08	3.58E+07

Table A5. Varying Ice Speed in X-Axis

RPM	rad/sec	Stress on Propeller (Pa)	Stress on Ice Block (Pa)
0	0	7.59E+07	1.86E+06
25	2.617994	8.32E+07	2.00E+06
50	5.235988	9.22E+07	2.20E+06
75	7.853982	9.97E+07	2.41E+06
100	10.47198	1.05E+08	2.58E+06
125	13.08997	1.12E+08	2.74E+06
150	15.70796	1.18E+08	2.91E+06

Table A6. Varying Propeller Rotation in Z-Axis

RPM	rad/sec	Stress on Propeller (Pa)	Stress on Ice Block (Pa)
0	0	1.12E+08	1.87E+06
50	5.235988	1.11E+08	1.85E+06
75	7.853982	1.10E+08	1.83E+06
100	10.47198	1.09E+08	1.81E+06
125	13.08997	1.07E+08	1.79E+06
150	15.70796	1.05E+08	1.77E+06

Table A7. Varying Propeller Rotation in Y-Axis

RPM	rad/sec	Stress on Propeller (Pa)	Stress on Ice Block (Pa)
0	0	3.55E+07	9.23E+06
50	5.235988	3.59E+07	9.29E+06
75	7.853982	3.62E+07	9.32E+06
100	10.47198	3.64E+07	9.34E+06
125	13.08997	3.65E+07	9.35E+06
150	15.70796	3.67E+07	9.36E+06

Table A8. Varying Propeller Rotation in X-Axis

Translating (m/s)	Knots	RPM	Stress on Propeller (Pa)	Stress on Ice Block (Pa)
2	3.886	125	1.31E+08	2.76E+06
3	5.829	125	1.38E+08	2.70E+06
4	7.772	125	1.43E+08	2.60E+06
5	9.715	125	1.42E+08	2.50E+06

Table A9. Translating Propeller in Z-Axis

Translating (m/s)	Knots	RPM	Stress on Propeller (Pa)	Stress on Ice Block (Pa)
2	3.886	125	8.50E+07	1.24E+06
3	5.829	125	9.72E+07	1.27E+06
4	7.772	125	1.11E+08	1.34E+06
5	9.715	125	1.16E+08	1.35E+06

Table A10. Translating Propeller in Y-Axis

Translating (m/s)	Knots	RPM	Stress on Propeller (Pa)	Stress on Ice Block (Pa)
2	3.886	125	2.04E+08	3.57E+07
3	5.829	125	2.26E+08	3.92E+07
4	7.772	125	2.46E+08	4.26E+07
5	9.715	125	2.59E+08	4.56E+07

Table A11. Translating Propeller in X-Axis

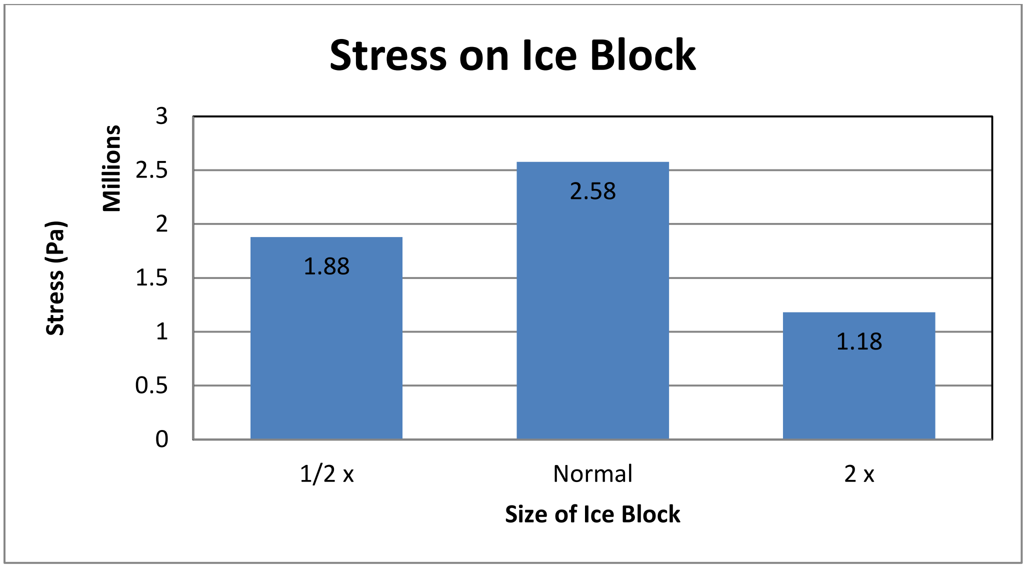

Figure A3. Varying Ice Block Size, Stress on Ice in Z-Axis

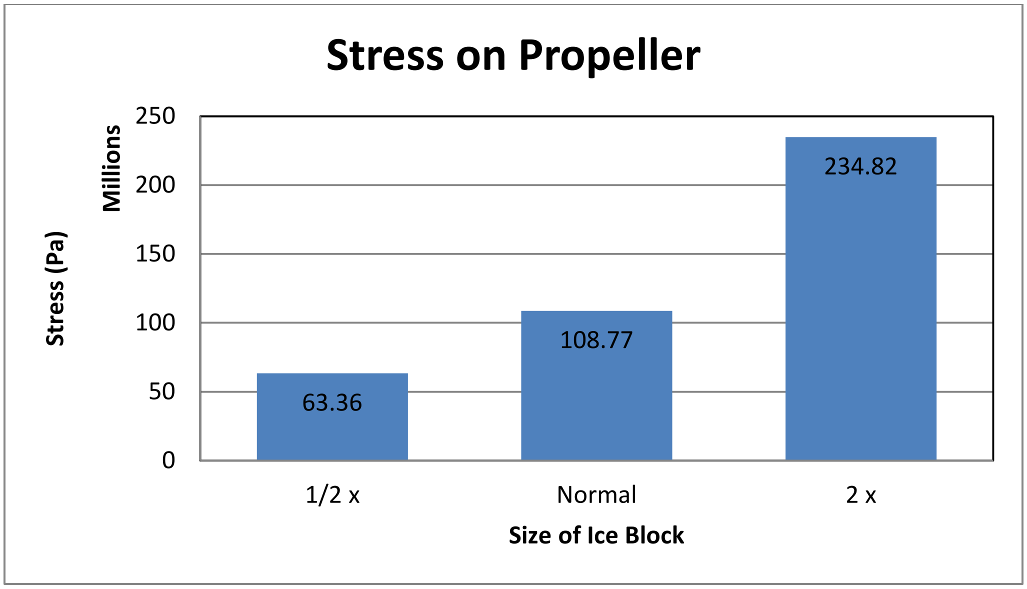

Figure A4. Varying Ice Block Size on Propeller in Y-Axis

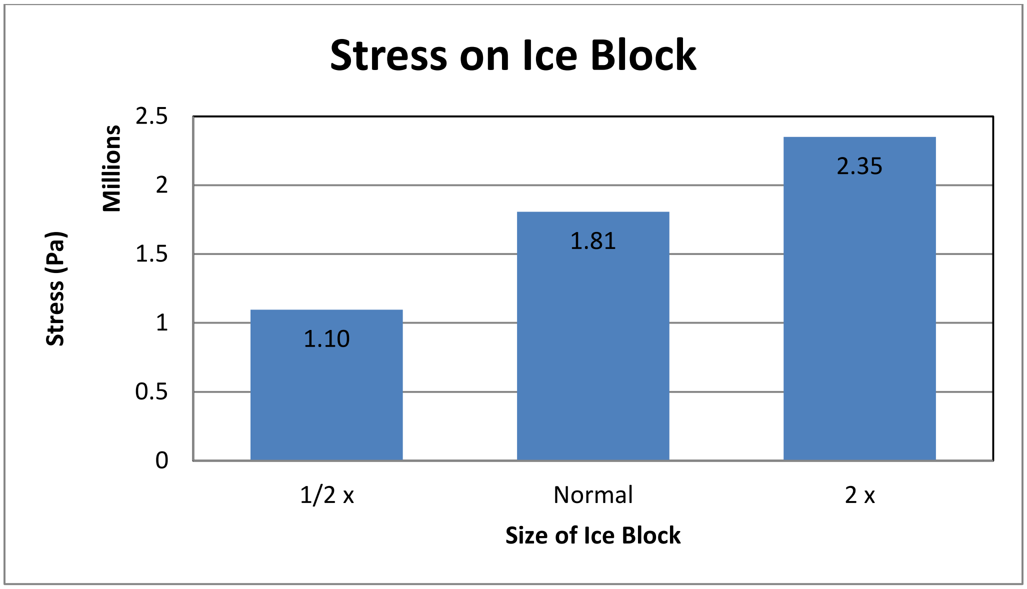

Figure A5. Varying Ice Block Size on Ice in Y-Axis

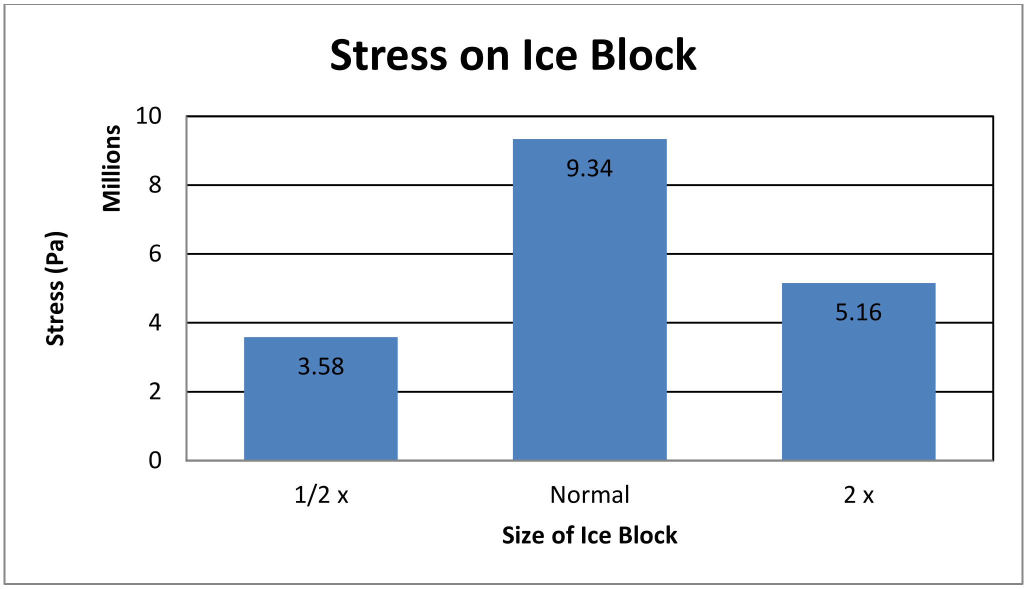

Figure A6. Varying Ice Block Size on Ice in X-Axis

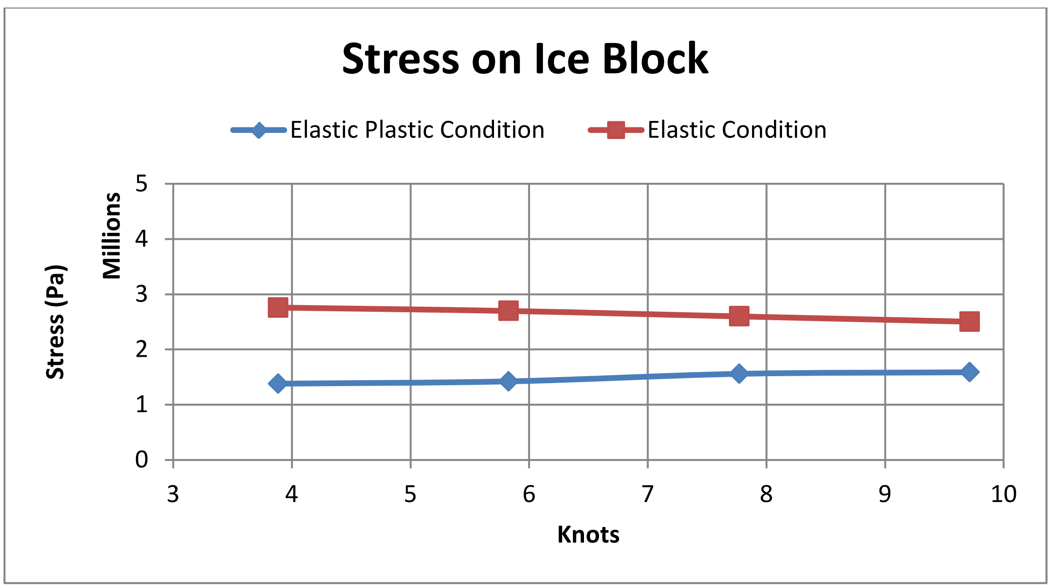

Figure A7. Ice Failure Model with Elastic Plastic Condition on Ice

APPENDIX B. SAMPLE EXPLICIT DYNAMICS REPORT FOR Y-AXIS

One of the many ANSYS reports extracted for ice impact in the Y-axis.

First Saved	Monday, June 10, 2013
Last Saved	Wednesday, June 19, 2013
Product Version	14.0 Release
Save Project Before Solution	No
Save Project After Solution	No

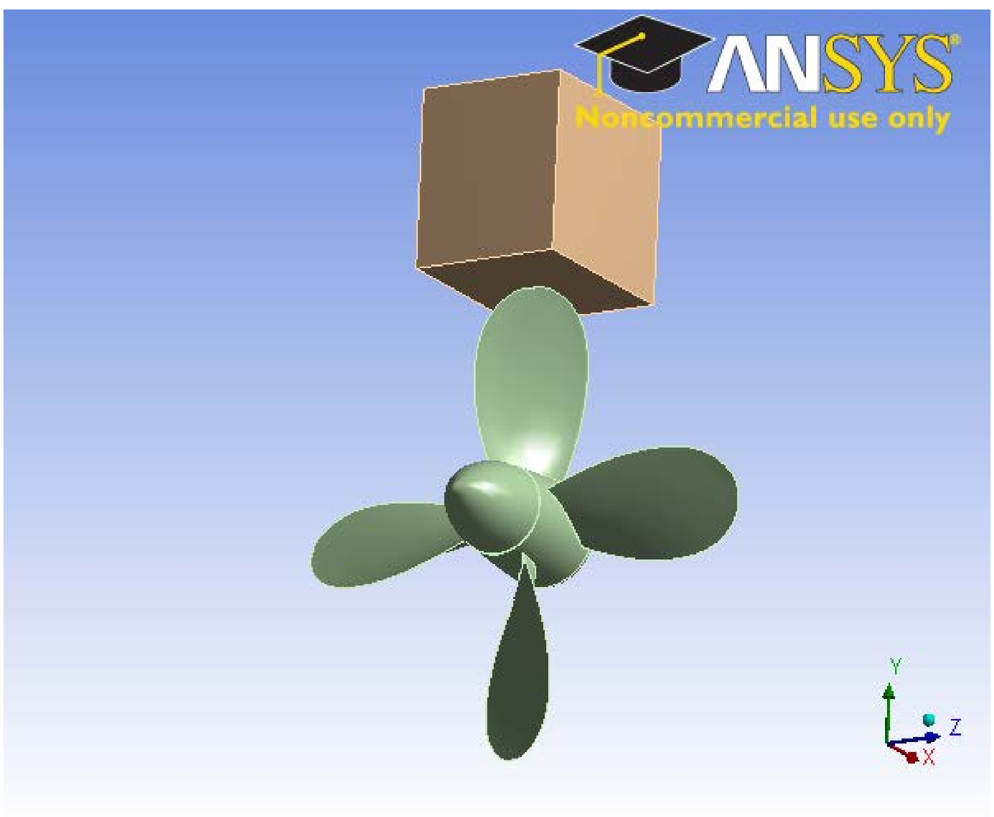

Figure B1. Ice Impact in Y-Axis

Unit System	Metric (m, kg, N, s, V, A) Degrees rad/s Celsius
Angle	Degrees
Rotational Velocity	rad/s
Temperature	Celsius

Table B1. Units

Object Name	*Geometry*
State	Fully Defined
Definition	
Source	C:\temp\Y-Direction\Ice_Moving2_files\dp0\Geom\DM\Geom.agdb
Type	DesignModeler
Length Unit	Meters
Element Control	Program Controlled
Display Style	Body Color
Bounding Box	
Length X	2.413e-002 m
Length Y	7.0059e-002 m
Length Z	5.0676e-002 m
Properties	
Volume	7.817e-006 m^3
Mass	1.6998e-002 kg
Scale Factor Value	1.
Statistics	
Bodies	2
Active Bodies	2
Nodes	3028
Elements	9485
Mesh Metric	None
Basic Geometry Options	
Parameters	Yes
Parameter Key	DS
Attributes	No
Named Selections	No
Material Properties	No
Advanced Geometry Options	
Use Associativity	Yes
Coordinate Systems	No
Reader Mode Saves Updated File	No
Use Instances	Yes
Smart CAD Update	No
Attach File Via Temp File	Yes

Object Name	*Geometry*
Temporary Directory	C:\Users\ggki1\AppData\Local\Temp
Analysis Type	3-D
Decompose Disjoint Faces	Yes
Enclosure and Symmetry Processing	Yes

Table B2. Model (B4, C4) > Geometry

Object Name	*Propeller*	*Ice Block*
State	Meshed	
Graphics Properties		
Visible	Yes	
Transparency	1	
Definition		
Suppressed	No	
Stiffness Behavior	Flexible	
Coordinate System	Default Coordinate System	
Reference Temperature	By Environment	
Reference Frame	Lagrangian	
Material		
Assignment	Stainless Steel NL	Sea Ice
Nonlinear Effects	Yes	
Thermal Strain Effects	Yes	
Bounding Box		
Length X	1.905e-002 m	2.032e-002 m
Length Y	5.0676e-002 m	1.9304e-002 m
Length Z	5.0676e-002 m	1.6256e-002 m
Properties		
Volume	1.4405e-006 m³	6.3765e-006 m³
Mass	1.1164e-002 kg	5.8345e-003 kg
Centroid X	-1.8335e-003 m	0. m
Centroid Y	-3.8815e-009 m	3.5069e-002 m
Centroid Z	-6.0579e-008 m	0. m
Moment of Inertia Ip1	7.5784e-007 kg·m²	3.0967e-007 kg·m²
Moment of Inertia Ip2	5.9012e-007 kg·m²	3.2924e-007 kg·m²
Moment of Inertia Ip3	5.9012e-007 kg·m²	3.8194e-007 kg·m²
Statistics		
Nodes	2038	990
Elements	8765	720
Mesh Metric	None	

Table B3. Model (B4, C4) > Geometry > Parts

Object Name	*Global Coordinate System*	*Coordinate System*
State	Fully Defined	
Definition		
Type	Cartesian	Cylindrical
Coordinate System ID	0.	
Coordinate System		Program Controlled
Origin		
Origin X	0. m	-1.8335e-003 m
Origin Y	0. m	-3.8815e-009 m
Origin Z	0. m	-6.0579e-008 m
Define By		Geometry Selection
Geometry		Defined
Directional Vectors		
X Axis Data	[1. 0. 0.]	[0. 0. -1.]
Y Axis Data	[0. 1. 0.]	
Z Axis Data	[0. 0. 1.]	[1. 0. 0.]
Principal Axis		
Axis		Z
Define By		Global X Axis
Orientation About Principal Axis		
Axis		Y
Define By		Default
Transformations		
Base Configuration		Absolute
Transformed Configuration		[-1.8335e-003 -3.8815e-009 -6.0579e-008]

Table B4. Model (B4, C4) > Geometry > Parts > Coordinate System

Object Name	*Connections*
State	Fully Defined
Auto Detection	
Generate Automatic Connection On Refresh	Yes
Transparency	
Enabled	Yes

Table B5. Model (B4, C4) > Connections

Object Name	*Contacts*
State	Fully Defined
Definition	
Connection Type	Contact
Scope	
Scoping Method	Geometry Selection

Geometry	All Bodies
Auto Detection	
Tolerance Type	Slider
Tolerance Slider	0.
Tolerance Value	2.2442e-004 m
Use Range	No
Face/Face	Yes
Face/Edge	No
Edge/Edge	No
Priority	Include All
Group By	Bodies
Search Across	Bodies

Table B6. Model (B4, C4) > Connections > Contacts

Object Name	*Contact Region*
State	Fully Defined
Scope	
Scoping Method	Geometry Selection
Contact	2 Faces
Target	1 Face
Contact Bodies	Propeller
Target Bodies	Ice Block
Definition	
Type	Bonded
Scope Mode	Automatic
Behavior	Program Controlled
Maximum Offset	1.e-007 m
Breakable	No
Suppressed	No
Advanced	
Formulation	Program Controlled
Detection Method	Program Controlled
Normal Stiffness	Program Controlled
Update Stiffness	Program Controlled
Pinball Region	Program Controlled

Table B7. Model (B4, C4) > Connections > Contacts > Contact Regions

Object Name	*Body Interactions*
State	Fully Defined
Advanced	
Contact Detection	Trajectory

Formulation	Penalty
Body Self Contact	Yes
Element Self Contact	Yes
Tolerance	0.2

Table B8. Model (B4, C4) > Connections > Body Interactions

Object Name	*Body Interaction*
State	Fully Defined
Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Definition	
Type	Frictionless
Suppressed	No

Table B9. Model (B4, C4) > Connections > Body Interactions > Body Interaction

Object Name	*Mesh*
State	Solved
Defaults	
Physics Preference	Explicit
Relevance	10
Sizing	
Use Advanced Size Function	On: Fixed
Relevance Center	Medium
Initial Size Seed	Active Assembly
Smoothing	Medium
Transition	Slow
Min Size	Default (2.1228e-005 m)
Max Face Size	Default (2.1228e-003 m)
Max Size	Default (4.2457e-003 m)
Growth Rate	Default (1.19450)
Minimum Edge Length	1.261e-008 m
Inflation	
Use Automatic Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0.272
Maximum Layers	5
Growth Rate	1.2
Inflation Algorithm	Pre
View Advanced Options	No
Patch Conforming Options	

Triangle Surface Mesher	Program Controlled
Advanced	
Shape Checking	Explicit
Element Midside Nodes	Dropped
Straight Sided Elements	
Number of Retries	0
Extra Retries For Assembly	Yes
Rigid Body Behavior	Full Mesh
Mesh Morphing	Disabled
Defeaturing	
Pinch Tolerance	Default (1.9106e-005 m)
Generate Pinch on Refresh	No
Automatic Mesh Based Defeaturing	On
Defeaturing Tolerance	Default (1.0614e-005 m)
Statistics	
Nodes	3028
Elements	9485
Mesh Metric	None

Table B10. Model (B4, C4) > Mesh

Object Name	*Patch Conforming Method*
State	Fully Defined
Scope	
Scoping Method	Geometry Selection
Geometry	1 Body
Definition	
Suppressed	No
Method	Tetrahedrons
Algorithm	Patch Conforming
Element Midside Nodes	Use Global Setting

Table B11. Model (B4, C4) > Mesh > Mesh Controls

Object Name	*Static Structural (B5)*
State	Solved
Definition	
Physics Type	Structural
Analysis Type	Static Structural
Solver Target	Mechanical APDL
Options	
Environment Temperature	22. °C
Generate Input Only	No

Table B12. Model (B4, C4) > Analysis

Object Name	*Analysis Settings*
State	Fully Defined
Step Controls	
Number Of Steps	1.
Current Step Number	1.
Step End Time	1. s
Auto Time Stepping	Program Controlled
Solver Controls	
Solver Type	Program Controlled
Weak Springs	Program Controlled
Large Deflection	Off
Inertia Relief	Off
Restart Controls	
Generate Restart Points	Program Controlled
Retain Files After Full Solve	No
Nonlinear Controls	
Force Convergence	Program Controlled
Moment Convergence	Program Controlled
Displacement Convergence	Program Controlled
Rotation Convergence	Program Controlled
Line Search	Program Controlled
Stabilization	Off
Output Controls	
Stress	Yes
Strain	Yes
Nodal Forces	No
Contact Miscellaneous	No
General Miscellaneous	No
Calculate Results At	All Time Points
Max Number of Result Sets	Program Controlled
Analysis Data Management	
Solver Files Directory	C:\temp\Y-Direction\Ice_Moving2_files\dp0\SYS\MECH\
Future Analysis	None
Scratch Solver Files Directory	
Save MAPDL db	No
Delete Unneeded Files	Yes
Nonlinear Solution	Yes
Solver Units	Active System
Solver Unit System	mks

Table B13. Model (B4, C4) > Static Structural (B5) > Analysis Settings

Object Name	*Rotational Velocity*
State	Fully Defined
Scope	
Scoping Method	Geometry Selection
Geometry	1 Body
Definition	
Define By	Components
Coordinate System	Global Coordinate System
X Component	-10.471 rad/s (ramped)
Y Component	0. rad/s (ramped)
Z Component	0. rad/s (ramped)
X Coordinate	0. m
Y Coordinate	0. m
Z Coordinate	0. m
Suppressed	No

Table B14. Model (B4, C4) > Static Structural (B5) > Rotations

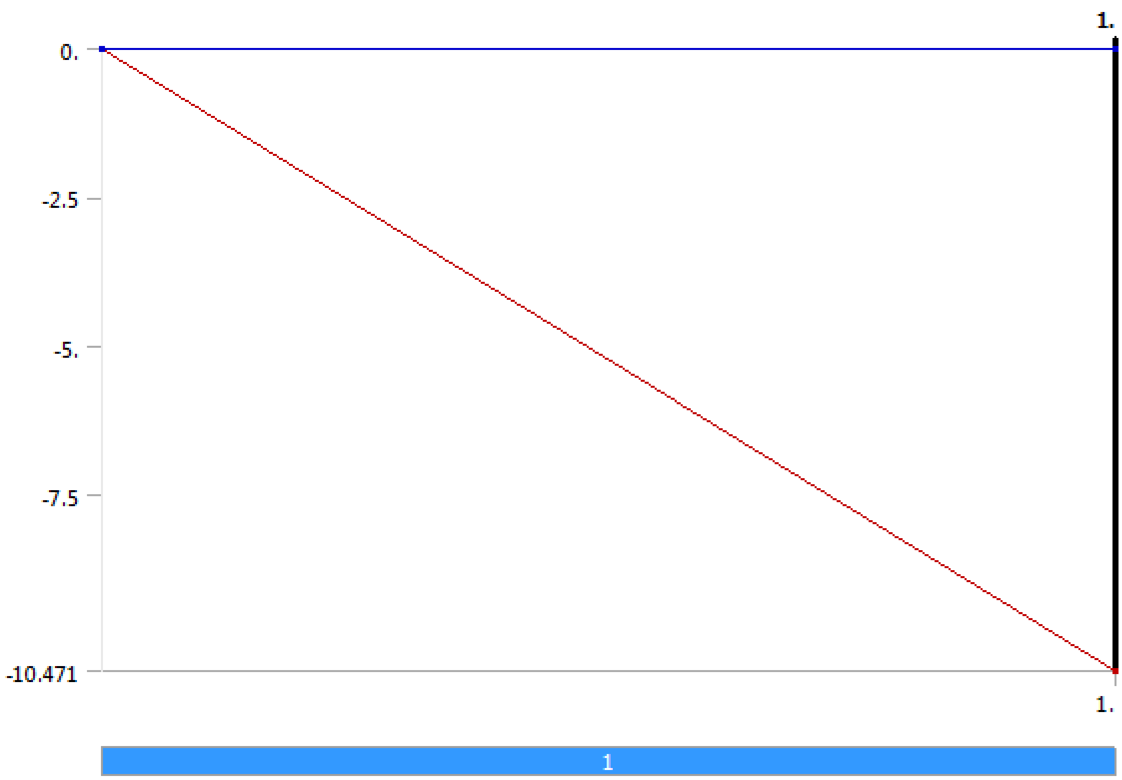

Figure B2. Model (B4, C4) > Static Structural (B5) > Rotational Velocity

Object Name	*Fixed Support*	*Fixed Support 2*
State	Fully Defined	
Scope		
Scoping Method	Geometry Selection	
Geometry	3 Faces	1 Face
Definition		
Type	Fixed Support	
Suppressed	No	

Table B15. Model (B4, C4) > Static Structural (B5) > Loads

Object Name	*Solution (B6)*
State	Solved
Adaptive Mesh Refinement	
Max Refinement Loops	1.
Refinement Depth	2.
Information	
Status	Done

Table B16. Model (B4, C4) > Static Structural (B5) > Solution

Object Name	*Solution Information*
State	Solved
Solution Information	
Solution Output	Solver Output
Newton-Raphson Residuals	0
Update Interval	2.5 s
Display Points	All
FE Connection Visibility	
Activate Visibility	Yes
Display	All FE Connectors
Draw Connections Attached To	All Nodes
Line Color	Connection Type
Visible on Results	No
Line Thickness	Single
Display Type	Lines

Table B17. Model (B4, C4) > Static Structural (B5) > Solution (B6) > Solution Information

Object Name	*Equivalent Stress*
State	Solved
Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Definition	
Type	Equivalent (von-Mises) Stress
By	Time
Display Time	Last
Calculate Time History	Yes
Identifier	
Suppressed	No
Integration Point Results	
Display Option	Averaged
Results	
Minimum	7.0565e-004 Pa
Maximum	207.6 Pa
Minimum Occurs On	Ice Block
Maximum Occurs On	Propeller
Minimum Value Over Time	
Minimum	1.3355e-004 Pa
Maximum	7.0565e-004 Pa
Maximum Value Over Time	
Minimum	8.3049 Pa
Maximum	207.6 Pa
Information	
Time	1. s
Load Step	1
Substep	4
Iteration Number	4

Table B18. Model (B4, C4) > Static Structural (B5) > Solution (B6) > Results

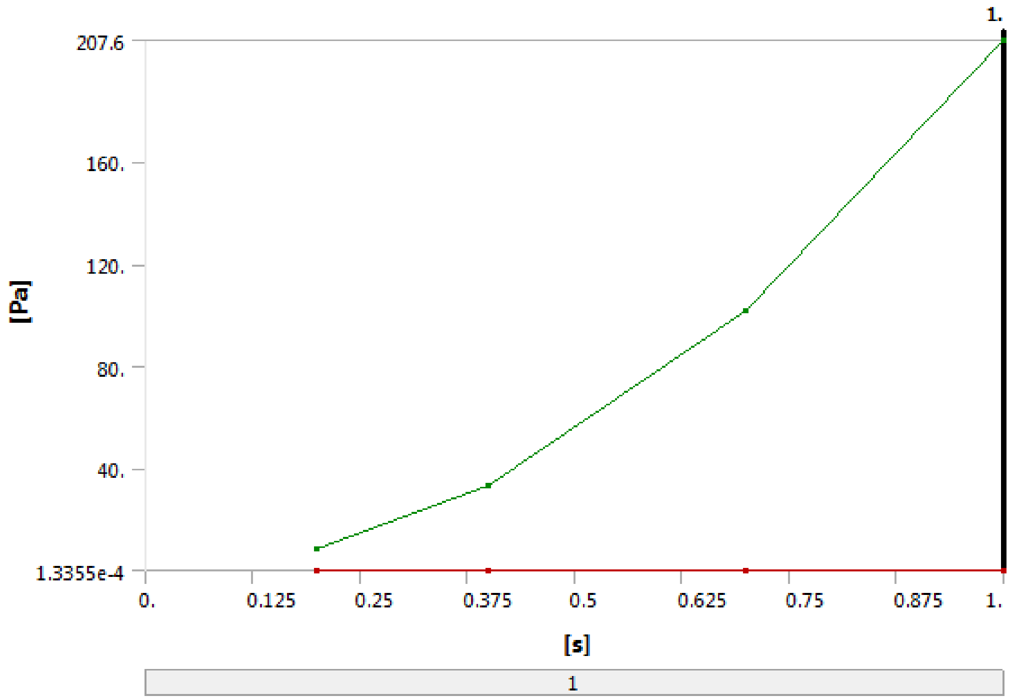

Figure B3. Model (B4, C4) > Static Structural (B5) > Solution (B6) > Equivalent Stress

Time [s]	Minimum [Pa]	Maximum [Pa]
0.2	1.8751e-004	8.3049
0.4	1.3355e-004	33.216
0.7	3.5444e-004	101.73
1.	7.0565e-004	207.6

Table B1. Model (B4, C4) > Static Structural (B5) > Solution (B6) > Equivalent Stress

Object Name	*Explicit Dynamics (C5)*
State	Solved
Definition	
Physics Type	Structural
Analysis Type	Explicit Dynamics
Solver Target	AUTODYN
Options	
Environment Temperature	22. °C
Generate Input Only	No

Table B20 Model (B4, C4) > Analysis

Object Name	*Initial Conditions*
State	Fully Defined

Table B21. Model (B4, C4) > Explicit Dynamics (C5) > Initial Conditions

Object Name	*Pre-Stress (Static Structural)*	*Velocity*	*Angular Velocity*
State	Fully Defined		
Definition			
Pre-Stress Environment	Static Structural		
Mode	Material State		
Time	End Time		
Input Type		Velocity	Angular Velocity
Define By		Components	
Coordinate System		Global Coordinate System	
X Component		0. m/s	-10.471 rad/s
Y Component		-0.5 m/s	0. rad/s
Z Component		0. m/s	0. rad/s
Suppressed		No	
Scope			
Scoping Method		Geometry Selection	
Geometry		1 Body	

Table B22 Model (B4, C4) > Explicit Dynamics (C5) > Initial Conditions > Initial Condition

Object Name	*Analysis Settings*
State	Fully Defined
Step Controls	
Resume From Cycle	0
Maximum Number of Cycles	1e+07
End Time	4.e-004 s
Maximum Energy Error	0.1
Reference Energy Cycle	0
Initial Time Step	Program Controlled
Minimum Time Step	Program Controlled
Maximum Time Step	Program Controlled
Time Step Safety Factor	0.9
Characteristic Dimension	Diagonals
Automatic Mass Scaling	No
Solver Controls	
Precision	Double
Solve Units	mm, mg, ms
Beam Solution Type	Bending
Beam Time Step Safety Factor	0.5
Hex Integration Type	Exact

Shell Sublayers	3
Shell Shear Correction Factor	0.8333
Shell BWC Warp Correction	Yes
Shell Thickness Update	Nodal
Tet Integration	Average Nodal Pressure
Shell Inertia Update	Recompute
Density Update	Program Controlled
Minimum Velocity	1.e-006 m s^-1
Maximum Velocity	1.e+010 m s^-1
Radius Cutoff	1.e-003
Euler Domain Controls	
Domain Size Definition	Program Controlled
Display Euler Domain	Yes
Scope	All Bodies
X Scale factor	1.2
Y Scale factor	1.2
Z Scale factor	1.2
Domain Resolution Definition	Total Cells
Total Cells	2.5e+05
Lower X Face	Flow Out
Lower Y Face	Flow Out
Lower Z Face	Flow Out
Upper X Face	Flow Out
Upper Y Face	Flow Out
Upper Z Face	Flow Out
Euler Tracking	By Body
Damping Controls	
Linear Artificial Viscosity	0.2
Quadratic Artificial Viscosity	1.
Linear Viscosity in Expansion	No
Hourglass Damping	AUTODYN Standard
Viscous Coefficient	0.1
Static Damping	0.
Erosion Controls	
On Geometric Strain Limit	Yes
Geometric Strain Limit	1.5
On Material Failure	No
On Minimum Element Time Step	No
Retain Inertia of Eroded Material	Yes
Output Controls	
Save Results on	Equally Spaced Points
Number of points	20
Save Restart Files on	Equally Spaced Points
Number of points	5
Save Result Tracker Data on	Cycles
Cycles	1
Analysis Data Management	

Solver Files Directory	C:\temp\Y-Direction\Ice_Moving2_files\dp0\SYS-1\MECH\
Scratch Solver Files Directory	

Table B23. Model (B4, C4) > Explicit Dynamics (C5) > Analysis Settings

Object Name	*Solution (C6)*
State	Solved
Information	
Status	Done

Table B24. Model (B4, C4) > Explicit Dynamics (C5) > Solution

Object Name	*Solution Information*
State	Solved
Solution Information	
Solution Output	Solver Output
Update Interval	2.5 s
Display Points	All
Display Filter During Solve	Yes

Table B26. Model (B4, C4) > Explicit Dynamics (C5) > Solution (C6) > Solution Information

Object Name	*Equivalent Stress*	*Equivalent Stress 2*	*Equivalent Stress 3*
State	Solved		
Scope			
Scoping Method	Geometry Selection		
Geometry	All Bodies	3 Faces	1 Face
Definition			
Type	Equivalent (von-Mises) Stress		
By	Time		
Display Time	Last	2.4e-004 s	3.5301e-004 s
Calculate Time History	Yes		
Identifier			
Suppressed	No		
Integration Point Results			
Display Option	Averaged		
Results			
Minimum	312.12 Pa	1.2566e+005 Pa	2472.1 Pa
Maximum	1.323e+007 Pa	1.0877e+008 Pa	17760 Pa
Minimum Occurs On	Ice Block		
Maximum Occurs On	Propeller		
Minimum Value Over Time			
Minimum	8.6014e-004 Pa	1.3128 Pa	1.1981e-003 Pa

Maximum	5231.8 Pa	1.2566e+005 Pa	13097 Pa
Maximum Value Over Time			
Minimum	223.44 Pa	164.19 Pa	8.8105e-002 Pa
Maximum	1.0877e+008 Pa		1.8079e+006 Pa
Information			
Time	4.e-004 s	2.4e-004 s	3.6e-004 s
Set	21	13	19

Table B26. Model (B4, C4) > Explicit Dynamics (C5) > Solution (C6) > Results

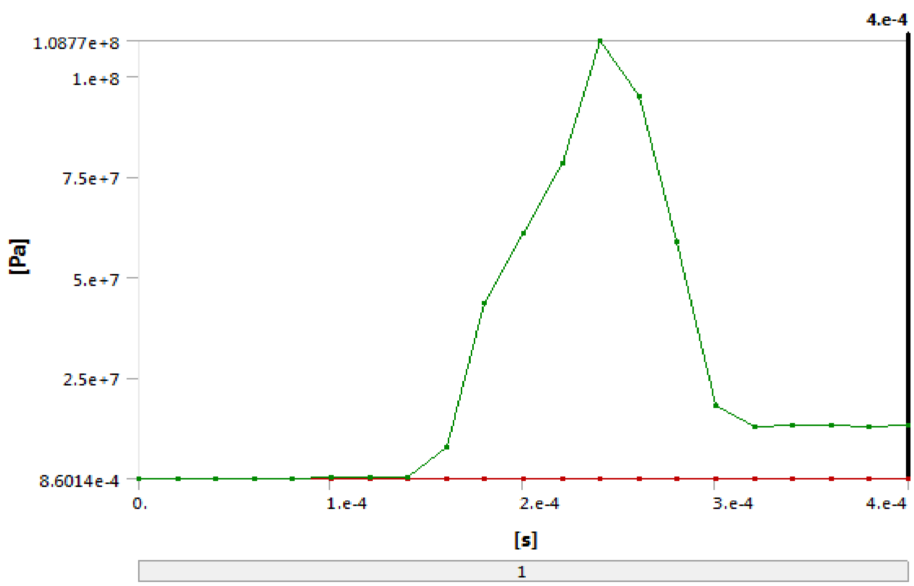

Figure B4. Model (B4, C4) > Explicit Dynamics (C5) > Solution (C6) > Equivalent Stress

Time [s]	Minimum [Pa]	Maximum [Pa]
1.1755e-038	8.6014e-004	223.44
2.e-005		22538
4.e-005		31923
6.e-005		72122
8.e-005		1.2428e+005
1.e-004		2.0103e+005
1.2e-004		2.9256e+005
1.4e-004		3.8095e+005
1.6e-004		7.6995e+006
1.8e-004	3687.9	4.3758e+007
2.e-004	1125.9	6.1112e+007
2.2e-004	1937.2	7.8533e+007
2.4e-004	3536.4	1.0877e+008

2.6e-004	5231.8	9.5143e+007
2.8e-004	2760.9	5.8749e+007
3.e-004	2208.9	1.8095e+007
3.2e-004	1340.	1.2972e+007
3.4e-004	1637.	1.3213e+007
3.6e-004	801.95	1.3195e+007
3.8e-004	974.18	1.2991e+007
4.e-004	312.12	1.323e+007

Table B27. Model (B4, C4) > Explicit Dynamics (C5) > Solution (C6) > Equivalent Stress

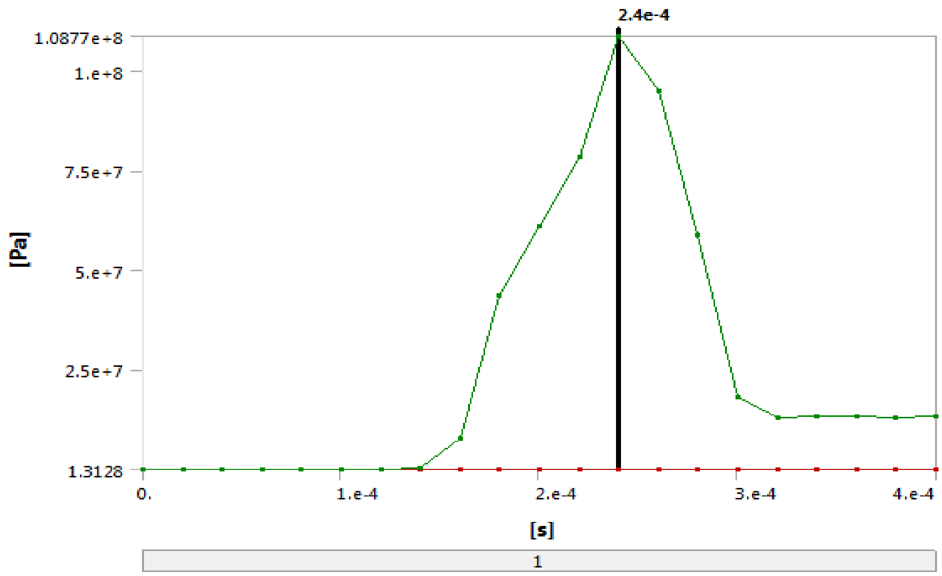

Figure B5. Model (B4, C4) > Explicit Dynamics (C5) > Solution (C6) > Equivalent Stress 2

Time [s]	Minimum [Pa]	Maximum [Pa]
1.1755e-038	1.3128	164.19
2.e-005	1.5762	10288
4.e-005	1.9942	18109
6.e-005	3.0218	34545
8.e-005	532.17	59235
1.e-004	1776.3	95527
1.2e-004	5901.7	1.4171e+005
1.4e-004	5624.3	2.2086e+005
1.6e-004	7405.1	7.6995e+006
1.8e-004	40863	4.3758e+007
2.e-004	67104	6.1112e+007

2.2e-004	72364	7.8533e+007
2.4e-004	1.2566e+005	1.0877e+008
2.6e-004	67654	9.5143e+007
2.8e-004	61505	5.8749e+007
3.e-004	20232	1.8095e+007
3.2e-004	54456	1.2972e+007
3.4e-004	65622	1.3213e+007
3.6e-004	62536	1.3195e+007
3.8e-004	40645	1.2991e+007
4.e-004	57830	1.323e+007

Table B28. Model (B4, C4) > Explicit Dynamics (C5) > Solution (C6) > Equivalent Stress 2

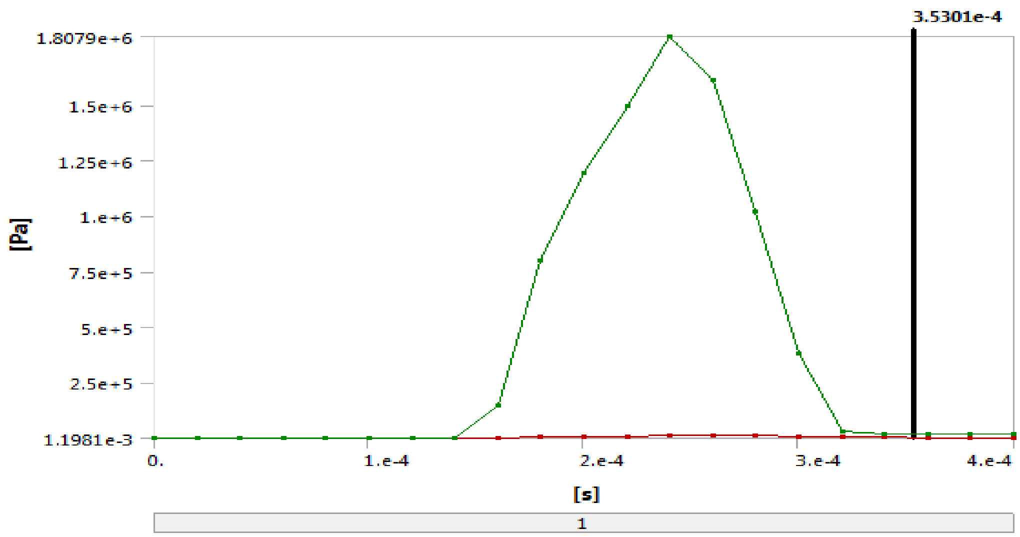

Figure B6. Model (B4, C4) > Explicit Dynamics (C5) > Solution (C6) > Equivalent Stress 3

<table>
<tr><th>Time [s]</th><th>Minimum [Pa]</th><th>Maximum [Pa]</th></tr>
<tr><td>1.1755e-038</td><td rowspan="9">1.1981e-003</td><td rowspan="8">8.8105e-002</td></tr>
<tr><td>2.e-005</td></tr>
<tr><td>4.e-005</td></tr>
<tr><td>6.e-005</td></tr>
<tr><td>8.e-005</td></tr>
<tr><td>1.e-004</td></tr>
<tr><td>1.2e-004</td></tr>
<tr><td>1.4e-004</td></tr>
<tr><td>1.6e-004</td><td>1.4551e+005</td></tr>
<tr><td>1.8e-004</td><td>6924.6</td><td>8.007e+005</td></tr>
<tr><td>2.e-004</td><td>7975.2</td><td>1.196e+006</td></tr>
</table>

2.2e-004	7570.	1.4959e+006
2.4e-004	10732	1.8079e+006
2.6e-004	13097	1.6089e+006
2.8e-004	10555	1.0217e+006
3.e-004	6273.6	3.7954e+005
3.2e-004	3613.6	33084
3.4e-004	3569.7	18972
3.6e-004	2472.1	17760
3.8e-004	1937.6	16258
4.e-004	2685.	17388

Table B29. Model (B4, C4) > Explicit Dynamics (C5) > Solution (C6) > Equivalent Stress 3

Density	7750 kg m^-3
Specific Heat	480 J kg^-1 C^-1

Table B30. Stainless Steel NL > Constants

Temperature C	Young's Modulus Pa	Poisson's Ratio	Bulk Modulus Pa	Shear Modulus Pa
	1.93e+011	0.31	1.693e+011	7.3664e+010

Table B31. Stainless Steel NL > Isotropic Elasticity

Yield Strength Pa	Tangent Modulus Pa	Temperature C
2.1e+008	1.8e+009	

Table B32. Stainless Steel NL > Bilinear Isotropic Hardening

Density	915 kg m^-3

Table B33. Sea Ice > Constants

Temperature C	Young's Modulus Pa	Poisson's Ratio	Bulk Modulus Pa	Shear Modulus Pa
	2.e+009	0.295	1.626e+009	7.722e+008

Table B34. Sea Ice > Isotropic Elasticity

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